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DETERMINATION OF THE COMBUSTION AND HEAT TRANSFER CHARACTERISTICS OF CBDC COAL-WATER MIXTURE (CWM) IN COMPARISON TO HEAVY FUEL OIL

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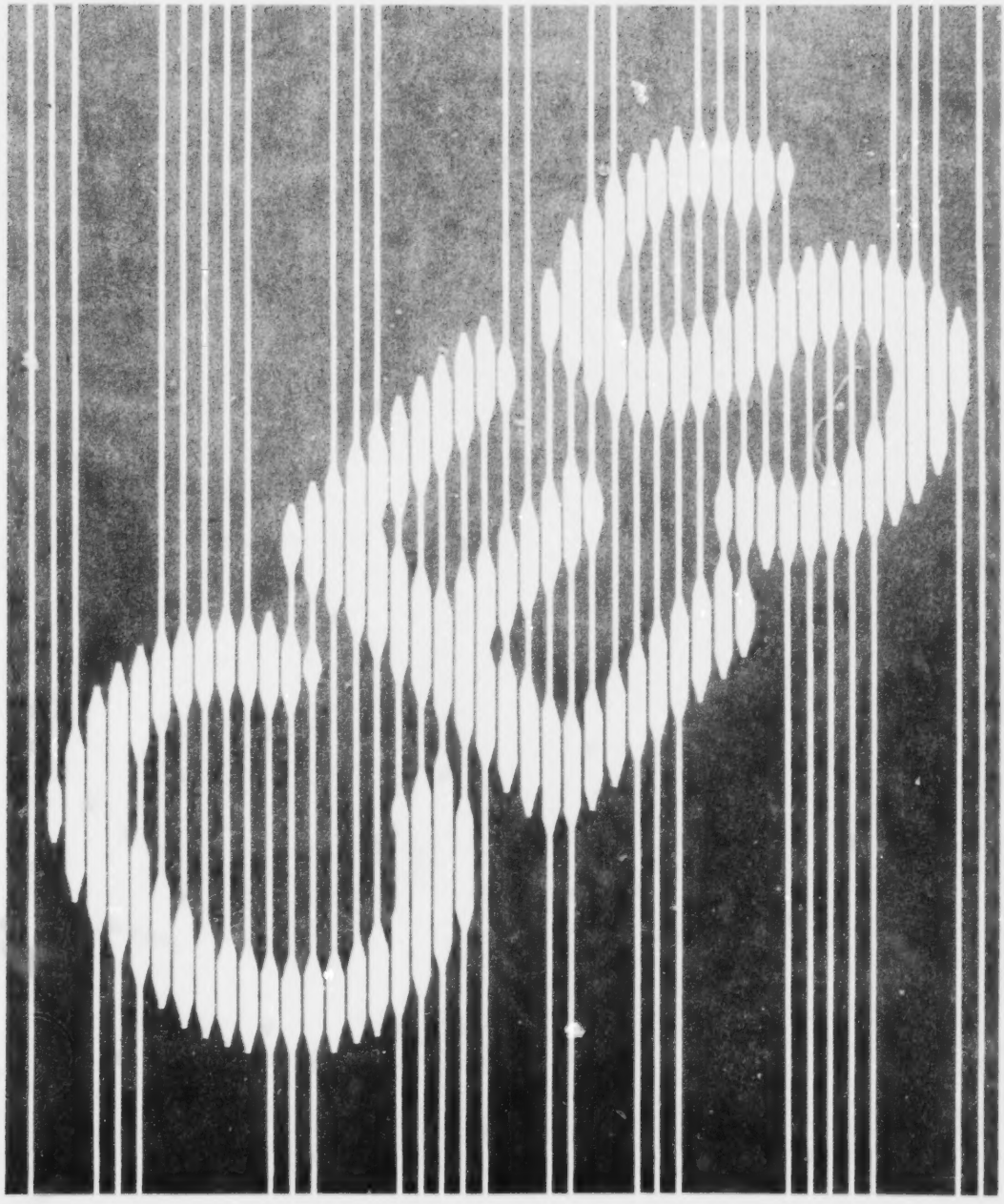

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DETERMINATION OF THE COMBUSTION AND HEAT TRANSFER CHARACTERISTICS OF CBDC COAL-WATER MIXTURE (CWM) IN COMPARISON TO HEAVY FUEL OIL

by

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A report of scientific work carried out under
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MICROMEDIA

To travel hopefully is a better thing
than to arrive, and the true success
is to labour.

Robert Louis Stevenson
(1850-1894)

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SUMMARY

This report describes the experimental procedures and results of a series of tests to determine the combustion and heat transfer characteristics of heavy fuel oil (HFO) in comparison to coal water (CW) fuel. All the tests were performed in the Centre for Energy Studies (CES) combustion test facility located at the Technical University of Nova Scotia (TUNS). A thermal input of 1.8 MW was used for all tests and a furnace load of 0.81±0.1 MW (which corresponds to 44-46% of the thermal input) was maintained throughout the test program.

A potential second generation burner nozzle developed by the National Research Council of Canada (NRCC) was used. The variable geometry nozzle was designed to fire both HFO and CW and employed ceramics developed at the Atlantic Research Laboratories (ARL) of NRCC to overcome nozzle erosion. The nozzle performed satisfactorily for both fuels and no wear was observed.

Various in-flame measurements were made on fully optimised flames at two excess oxygen levels. Tests were also made on air and steam atomised flames. In addition, analytical tests were made on samples of in-flame particulates and deposited ash.

To ensure fully optimised flames, a number of pretests were made. Eight pretest flames are presented here as being representative of the various conditions and changes needed to ensure optimisation. During pretesting the combustion air swirl register was modified. Also, the divergent refractory burner throat was modified to give a half angle of divergence of 35° as compared to the original 21.4°. In addition, the length/diameter (L/D) ratio

was altered to give $1.0<L/D<1.5$. With these modifications stable type B flames were achieved using a 60° spray angle for HFO and a 50° spray angle for CW. Atomisation air/fuel and steam/fuel mass ratios were in the range 0.33-0.42 and 0.23-0.41 respectively.

The recirculation zone for a CW flame was found to be smaller than for a HFO flame. An examination of the axial flame temperature profiles shows that, although they are similar in shape, the peak temperature is higher and occurs closer to the atomiser in a heavy fuel oil flame. However, the flame temperatures were higher at the back end of the combustion chamber in the CW flame.

The oxygen concentration is initially lower in an oil flame while lower CO and SO_2 and higher NO_x are exhibited in a CW flame. High values of carbon burnout proved that the nozzle was atomising well. The carbon burnout was calculated using the formulae reported by Bortz et. al.[7] and was compared with the burnout calculated from the CO_2 concentration: the two methods correlated very well.

The heat flux characteristics of the two fuels were examined by measuring the radiant and total heat flux for each test flame. Similar trends are visible in the heat flux characteristics when comparing air and steam atomised HFO flames. For the CW tests, the air atomised 3% excess O_2 had higher values of heat flux than the test with 5% excess O_2 air atomised. The steam atomised test showed a more constant value of heat flux than any other test of this series.

The CW tests were compared with the HFO tests as well. With steam atomisation, a much higher peak heat release rate was seen with HFO than with CW. The 5% air atomised runs from both fuels showed higher values of heat flux close to the burner for the HFO flame. The magnitudes of the heat flux

dropped to almost the same value towards the end of the combustion chamber. Also, for CW flames, there is a more gradual drop in the heat flux for the CW flame along the tunnel.

Although the tests were of a short duration no erosion was observed on the atomiser components. A long term burn of the CW fuel and nozzle should be performed to complete the study. Various nozzles and fuels should be examined and compared so that the most up to date information on the burning of CW fuels would be available.

Eight appendicies are included with this report detailing the facilities available, test methods and measurements, results of calculations and the operator's log sheets and data from the five tests.

SOMMAIRE

Ce rapport decrit les procedures experimentales et les résultats d'une serie de test determinant les characteristiques de combustion et transfer de chaleur d'huile lourde (HFO) en comparaison au mélange charbon et eau (CW). Touts les tests ont été menés au laboratoire pour l'etude de la combustion au Centre for Energie Studies de l'Université Technique de la Nouvelle-Ecosse (TUNS). Une capacité thermique de 1.8 MW a été utiliseé pur tous les tests et une quantité chaudière de 0.81 ± 0.1 MW (ce qui correspond à une valeur de 44 à 40% de la capacité thermique) ont été maintenu durant tout le programme.

Aussi une bec d'un potentiel de deuxième genération fût utilise. Une bec géometrique variable at été conçu pur brûler autant HFO que CW et aussi ont été utilisées des ceramiques developpées aux Laboratoires de Recherches Atlantique (ARL) de NRCC afin d'éliminer l'érosion du bec. Le bec a donnée des résultats satisfaisant pour les deux combustibles et aucune usure fût obsersee.

Diners mesures à l'interieur de la flamme ont été prises à optimum aux deux mineaux d'oxigene en excès. Des tests ont été-aussi conduits sur l'air et la vapeur atomisés des flammes.

En plus, des tests analytiques ont été fait sur des échantillons de particules de l'interieur de la flamme et sur les dépots de cendres.

Pour assurer une flamme entièrement optimisée, une serie de pré-tests ont été conduits. Ici, hui de ces flammes sont presentées comme étant representatives de conditions variables et de changements nécessaires pour assurer l'optimization. Durant ces pré-tests l'instrument de registre du tourbillon d'air de combustion a été modifié. Aussi, la gorge du brûleur réfractaire divergent a été modifiée afin d'obtenir un angle divergent de 35° en comparaison du

original de 21.4°. En plus, le rapport longueur/diametre (L/D) a été modifé pour donner 1.0 < L/D < 1.5. Avec ces modifications une stabilité de flammes de type B a été obtenue en utilisant un jet d'un angle de 60° pour le (HFO) et un jet de 50° pour le (CW). Les rapports de la masse de l'automisation air/combustible et vapeur/combustible ont été de 0.33 à 0.42 et 0.23 à 0.41 rèspectinement.

La zone de recirculation pour une flamme (CW) a été trauveé plus petite que pour une flamme HFO. Une examination des profiles de l'axe de la temperature de la flamme démontre que, même si similaire en forme, la température de pointe est plus haute et arrive plus près de l'automiseur dans une flamme de combustion d'huile lourde. Par contre, les températures de flamme étaient plus hautes à l'arrière de la chambre de combustion dans une flamme CW.

La concentration d'oxigene initiallement plus basse dans une flamme à l'huile, alors que le CO et SO_2 plus bas et NO_x plus haut sont exibés dans une flamme CW. De hautes valeurs de brulage de carbone ont prové que le bec automisait efficacement. le brûlage de carbone a été calculé en utilisant la formule trauvé par Bortz et al.(7) et comparé avec le brûlage calculé à partir de concentration de CO_2: les deux methodes correspondaient très bien.

Les caracteristiques de flux de chaleur de deux combustibles ont été examinées en mesurant le radiant et le flut de chaleur total pour chacun des tests de flamme. Des tendances similaires sont visibles dans les caracteristiques de flux de chaleur quand les flammes atomisées par air et vapeur (HFO) sont comparées.

Pour les tests de CW, l'air atomisé 3% de O_2 en excès a une valeur plus haute de flux de chaleur que le test avec l'air atomisé 5% de O_2 en excès. Le test de vapeur atomisée a démontré une valeur plus constante de flux de chaleur que tout autre test de cette serie.

Les tests CW ont été aussi comparés avec les tests HFO. Avec la vapeur atomisée, un plus haute taux de relaches de châleur a été trouvé avec le HFO qu'avec le CW. Durant les tests d'air automisée à 5%, des deux combustibles démontrent des valeurs de flux de chaleur plus hautes près de l'atomiseur pour une flamme HFO. Les magnitudes des flux de chaleur sont tombés tout près de la même valeur pres de l'arrière de la chambre de combustion. Aussi, pour les flammes CW, il y a une tombée plus graduelle dans les flux de chaleur pour la flamme CW au long du tunnel.

Même si les tests étaient de courte durée, aucune erosion n'a été observee sur les composants de l'atomiseur un brûlage de longue durée du combustible CW avec ce bec devrait être conduit pour compléter cette étude. Aussi, différents becs et differents combustibles devraient être examinés et comparés pour qu'une information la plus actuelli soit desponsible.

Huit appendices sont inclus dans ce rapport détaillant les facilités disponibles, les methods et les mesures pour les tests, les resultats des calculations et le journal des operateurs ainsi que les donnés des cinq tests.

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NOMENCLATURE

$\dot{m}$	fuel mass burning rate / [kgs^{-1}]
r	radial distance from centerline of flame tunnel / [mm]
R	radius of flame tunnel / [mm]
z	axial distance from atomiser / [mm]
L	axial distance from tip of burner to back end of combustion chamber / [mm]
r/R	dimensionless radial position / [-]
R/R	computer generated title, synonymous with r/R as above
z/L	dimensionless axial position / [-]
Q	thermal input / [MW]
ΔH_c	net corrected calorific value / [$MJkg^{-1}$]
S	swirl number
L"/D	ratio of the axial length of the divergent section of the throat to the throat diameter before the divergent section / [-]
L'	distance from the breeching section to the collar on the windbox of the flame tunnel
l_g	length of the gun
d_i	depth of insertion of the gun; from the back end of the gun to the collar on the windbox
Z_i	distance from the throat exit to any point along the combustion chamber (as seen on the Flame tunnel Map fig. 2.1.)
Q_{TOT}	total heat flux
Q_{rad}	radiant heat flux

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Mark Twain wrote in Tom Sawyer:

> "Work consists of whatever a body is obliged to do...
> Play consists of whatever a body is not obliged to do."

The authors feel that in this case Mark Twain got it the wrong way round. We are indebted to the junior engineers and technicians of the Centre for Energy Studies who worked so hard to achieve the objectives of this test program: their long hours and patience are so much appreciated.

Finally, we wish to thank all the staff at the Centre for their help, encouragement and understanding, but especially our secretaries: without their tremendous effort the written report would be nothing.

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1. INTRODUCTION

The use of coal as a substitute for imported oil has been given a high priority by the Federal Government. Coal-liquid mixtures (CLM) appear to be a viable substitute for heavy fuel oil (HFO). Coal-water mixtures (CWM), in particular, appear to be prime candidates for replacing HFO in utility and large industrial boiler plants. Studies of coal beneficiation, properties and stability of coal-liquid mixtures, and coal slurry combustion have been undertaken.(1) However, until very recently there was a serious lack of detailed combustion and heat transfer data for coal-water flames.

The use of coal-liquid mixtures in units designed for oil-firing poses certain technological problems. Perhaps the most important concern is that of potential boiler derating (reduction in maximum attainable capacity). Babcock and Wilcox, Canada, undertook two studies(2,3) in which they attempted to estimate the extent of derating on four boiler configurations typical of eastern Canada. These studies(2,3) used conventional pulverised coal combustion data and reported(4) expected boiler performance-related derations resulting from coal-water slurry firing in oil-designed, wall-fired units in the range 39-59 percent: the use of such data makes the validity of the results suspect due to the inherent difference in the combustion and heat transfer characteristics of coal water fuels.

Recently detailed studies of coal-water flames have been conducted at the Canada Centre for Mineral and Energy Technology (CANMET) at a fuel firing rate of about 0.47 MW_{th} (1.6 MBtu hr^{-1})(5); the International Flame Research Foundation (IFRF) at IJmuiden at a fuel firing rate of about 2.5 MW_{th} (8.5 MBtu hr^{-1})(6,7); and full scale tests in a front wall-fired utility boiler,

originally designed for coal-firing, at Chatham, New Brunswick rated at 12.5 MW_e[8].

For the tests reported under this contract[a], a fuel firing rate of 1.8 MW_{th} (6.1 MBtu hr^{-1}) was used. Comparative studies on fully optimised heavy fuel oil and coal-water flames were made. These tests provide information at a firing rate intermediate between those used at CANMET and IFRF. The results from the previous and current tests should be of great help in planning the combustion tests proposed for the future. The next stage planned for a coal-water fired utility demonstration is the selection and testing of burners in a 20 MW_e oil-designed front wall-fired boiler at Charlottetown, P.E.I. which is hoped to be completed by mid-1985[8].

(a) DSS Contract 20ST. 23440-3-9224

2. TEST PROTOCOL

This section describes the flame types tested and the various measurements which were made. All the tests were carried out on fully optimised flames using a new ceramic nozzle developed by the National Research Council of Canada (NRCC). The details of the burner nozzle and gun assembly and the procedure of flame optimisation are described in detail in section three.

2.1 Test matrix

Five different flame types were tested. The test conditions and dates when they were performed are given in Table 2.1 This report will refer to the tests as numbers 1-5: this is for the convenience of a logical presentation and bears no relation to the chronological order as the CES code No. does. Test numbers 1, 2 and 4, 5 allow direct comparison between HFO and CW using

Table 2.1: Test matrix

Test No.	Conditions	Test Dates	CES Code No.
1	5% excess O_2, HFO air atomised	Aug. 7-9	FT37EMR
2	5% excess O_2, HFO steam atomised	Aug. 9-10	FT38EMR
3	3% excess O_2, CW air atomised	July 9-13	FT34EMR
4	5% excess O_2, CW air atomised	July 13-19	FT35EMR
5	5% excess O_2, CW steam atomised	July 19-20	FT36EMR

two atomisation mediums. Originally a test at 3% excess oxygen for HFO, air atomised, was planned, which would have given a direct comparison with test number 3. However, time and budgetary constraints did not permit this because of the development needed with the new nozzle and subsequent flame tunnel modifications to achieve fully optimised flame conditions.

Excess oxygen levels of 3 and 5% were chosen as being representative of large industrial and utility boiler plants respectively. Air atomised flames were studied to compare data with previous combustion testing. The tests at 5% excess oxygen were also run with steam atomisation which is normal practice in utility boilers.

2.2 Test measurements

All the combustion tests were performed in the Centre for Energy Studies' combustion test facility[9]. A detailed description of the facility is included in Appendix I. Once optimized conditions were achieved for each test condition, the following measurements were made:

(i) all normal operating parameters were logged;

(ii) fuel analysis;

(iii) in-flame measurements; and

(iv) photographic and video records.

At the end of each test, subsequent analyses of ash and in-flame particulates were performed in the coal research laboratory at TUNS.

2.2.1 Operating parameters

Throughout a test all normal operating parameters were logged at regular

intervals (usually every half hour) by the tunnel operator. Copies of the operators log sheets for each of the five tests are included in Appendix II.

Some parameters were logged to monitor the status of the system, for example fuel pressure and temperature at the pump in the HFO delivery system. Changes in these are indicative of fuel filter blockage or malfunction of the fuel preheaters. Others are the normal operating parameters, for example fuel pressure and temperature at the burner gun. Other parameters are related to flame stability, for example burner gun position. Finally, a set of parameters relating to flame conditions were logged, for example combustion air temperature and oxygen level. A number of the parameters are used to calculate other quantities, for example the fuel mass flow rate, in conjunction with the net corrected calorific value of the fuel enables calculation of the thermal input.

The parameters which were routinely logged are summarised in Table 2.2 along with their significance and classification. The calculation procedures used to determine necessary parameters derived from the logged parameters, for example thermal input, are described in detail in Appendix III.

2.2.2 Fuel analysis

Fuel samples were taken at regular intervals. For HFO, samples were taken from the pump bleed line. These samples were later analysed in the laboratory. Complete ultimate analyses were made. For CW, samples were taken from one of four locations, these were:

(1) day tank recirculation line (DTR);

Table 2.2: Routinely logged operating parameters

Parameter	Significance	Classification
1) Fuel pressure at pump	indicates any fuel filter plugging or air inleakage(a)	system
2) Fuel temperature at pump	indicates whether fuel heaters are functioning	status
3) Fuel pressure at burner	indicates nozzle blockage	
4) Fuel temperature at gun	enables control of fuel temberature (b)	
5) Fuel temperature at nozzle		
6) Atomisation medium pressure at the burner gun	indicates fuel pluggage and atomisation quality	
7) Air pressure at inlet to rotameter	enables calculation of corrected atomisation air flowrate	normal operating conditions
8) air temperature at rotameter		
9) Air flowrate		
10) Pressure drop across steam orifice	enables calculation of corrected atomisation steam flowrate and quality	
11) Pressure on steam main		
12) Pressure and temperature at throttling calorimeter		
13) Burner gun position	enables calculation of dimensionless axial location (Z/L)	flame stability parameters
14) Primary and secondary swirl settings		
15) Burner gun cooling air flowrate and pressure	enables calcuation of corrected cooling air flowrate	flame conditions
16) Combustion air temperature	enables calculation of corrected flow volumes	
17) Fuel mass flowrate	enables calculation of thermal input	
18) Pressure drop across air flow orifice	enables calculation of corrected air flowrate	
19) Furnace pressure	affects excess oxygen level	
20) Oxygen level	enables calculation of excess oxygen level	

(a) when using the Moyno progressive cavity pump with slurry fuels the pump speed is also noted.

(b) the NRCC gun contains a steam heater to enable fine adjustment of the fuel temperature.

(2) delivery line from forward tank (DFT);[a]

(3) delivery line from rear tank (DRT);[a] and

(4) rear tank recirculation line (RTR).

The CW fuel samples were subsequently analysed for solids/moisture ratio. One sample had a complete proximate, ultimate and rheological analysis performed. Further analyses were not performed because of the proprietary nature of the fuel. The analytical procedures are detailed in Appendix IV.

In this report fuel samples are coded F·X·Y where F denotes fuel; X the test number; and Y the sample number for that test. Table 2.3 summarises the fuel sample collection data.

2.2.3 In-flame measurements

Once steady-state conditions had been established, a number of in-flame measurements were made. The measurements and method by which they were made are summarised in Table 2.4. Detailed descriptions of the various experimental techniques are given in Appendix V. Due to a probe malfunction, the flame emissivity measurements were not made. Figure 2.1 shows the flame tunnel combustion chamber and the various measurement locations. The dimensionless axial position (Z/L) is a function of the fuel gun insertion depth. The zero position is taken as the tip of the burner nozzle. Figure 2.2 gives a nomograph which enables the dimensionless axial position to be calculated.

Tables 2.5 to 2.9 give the matrix of in-flame measurements which were made during each test. In addition to the in-flame measurements given in the

---

(a) The CW fuel was delivered in an insulated, but unheated, road tanker. The tanker had two compartments: a forward compartment (31 500 dm^3); and a rear compartment (13 500 dm^3).

matrix the temperature in the furnace exit breeching (furnace exit gas temperature), the particulate loading on the centreline of the exit breeching and the flue gas composition (CO, CO_2 and O_2) were measured.

Table 2.3: Fuel sample collection data

Sample No.	Date	Time	Location	Fuel Type	Coal Lab Sample No.
F.1.1	Aug 8	09:00	Pump	HFO	1306
F.1.2	Aug 9	08:45	Pump	HFO	1307
F.2.1	Aug 10	08:53	Pump	HFO	1308
F.3.1	July 9	14:15	DTR	CW	1277
F.3.2	July 10	09:04	DTR	CW	1278
F.3.3	July 10	12:20	DFT	CW	1279
F.3.4	July 11	10:15	DTR	CW	1280
F.3.5	July 12	08:40	DTR	CW	1282
F.3.6	July 13	10:00	DTR	CW	1283
F.3.7	July 19	12:35	DFT	CW	1288
F.4.1	July 16	10:00	DTR	CW	1284
F.4.2	July 17	10:50	DRT	CW	1285
F.4.3	July 17	13:15	DFT	CW	1286
F.4.4	July 18	11:40	RTR	CW	1287
F.5.1	July 19	19:30	RTR	CW	1289
F.5.2	July 20	01:07	DTR	CW	1290

Table 2.4: In-flame test measurements

Measurements	Method
1) Flame temperature	Suction pyrometer
2) Furnace exit gas temperature	Suction pyrometer
3) Flow boundaries	a) Hubbard probe for HFO b) Oxy-acetylene probe for CW
4) Gas and solids sampling within the flame and breeching	a) type B IFRF probe for CW b) type A and B IFRF probe for HFO
5) Total radiation	2π ellipsoidal radiometer
6) Total heat flux at furnace walls	2π total heat flux meter
7) Wall temperatures	In situ thermocouples
8) Visual record	VCR and 35mm colour photography

The majority of measuring devices that monitor tunnel operating parameters give readings in English units. During testing, when data reduction begins, these units are used exclusively throughout the calculations. The values reported here in S.I. are the conversions of the end result of the calculations made using English units.

The following diagrams are used by the test crews as aids in data reduction and, therefore, contain English units. They are presented here as an aid to visualisation of the measurement locations and the relations between the various measurements.

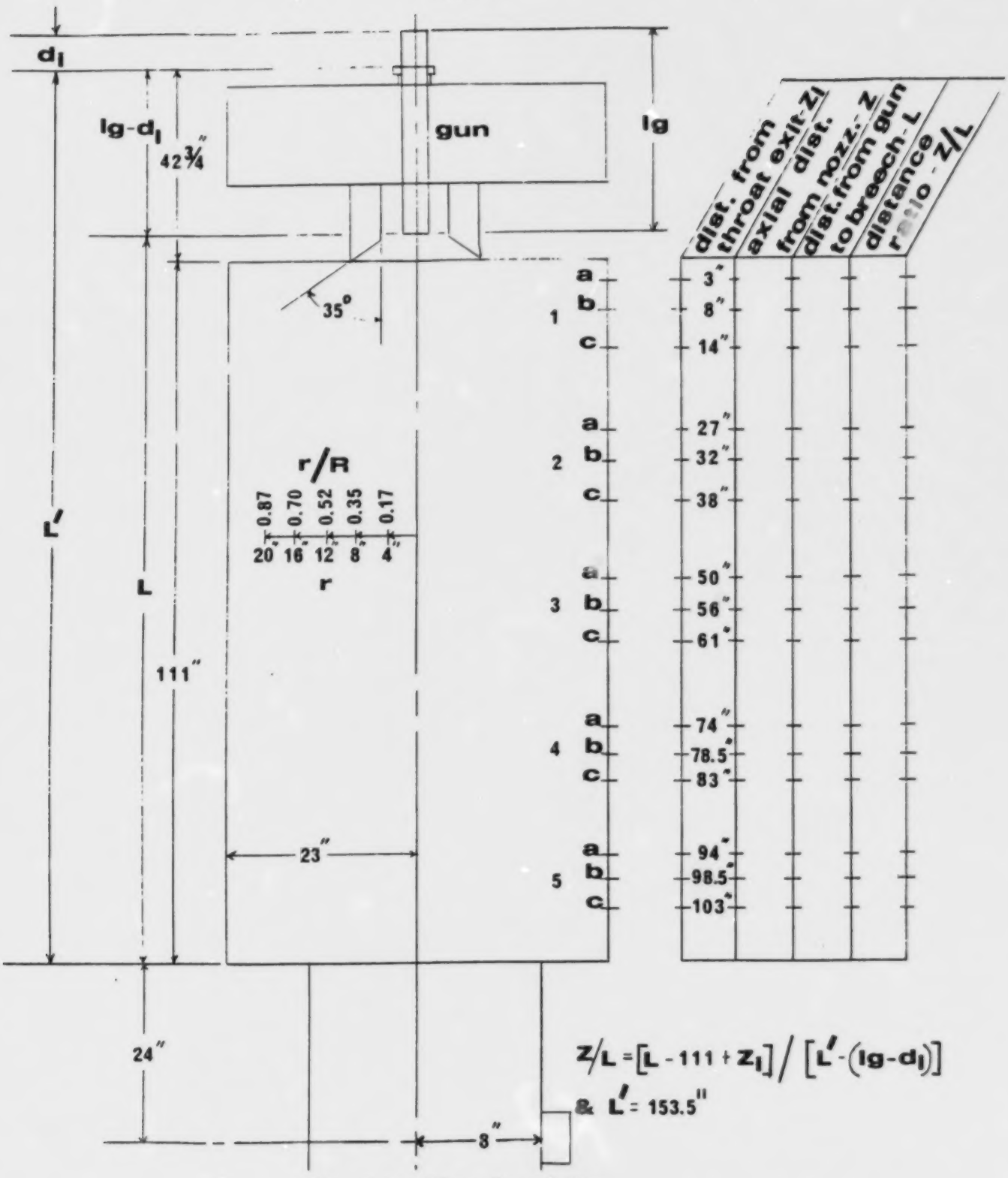


Fig. 2.1: Flame Tunnel Map

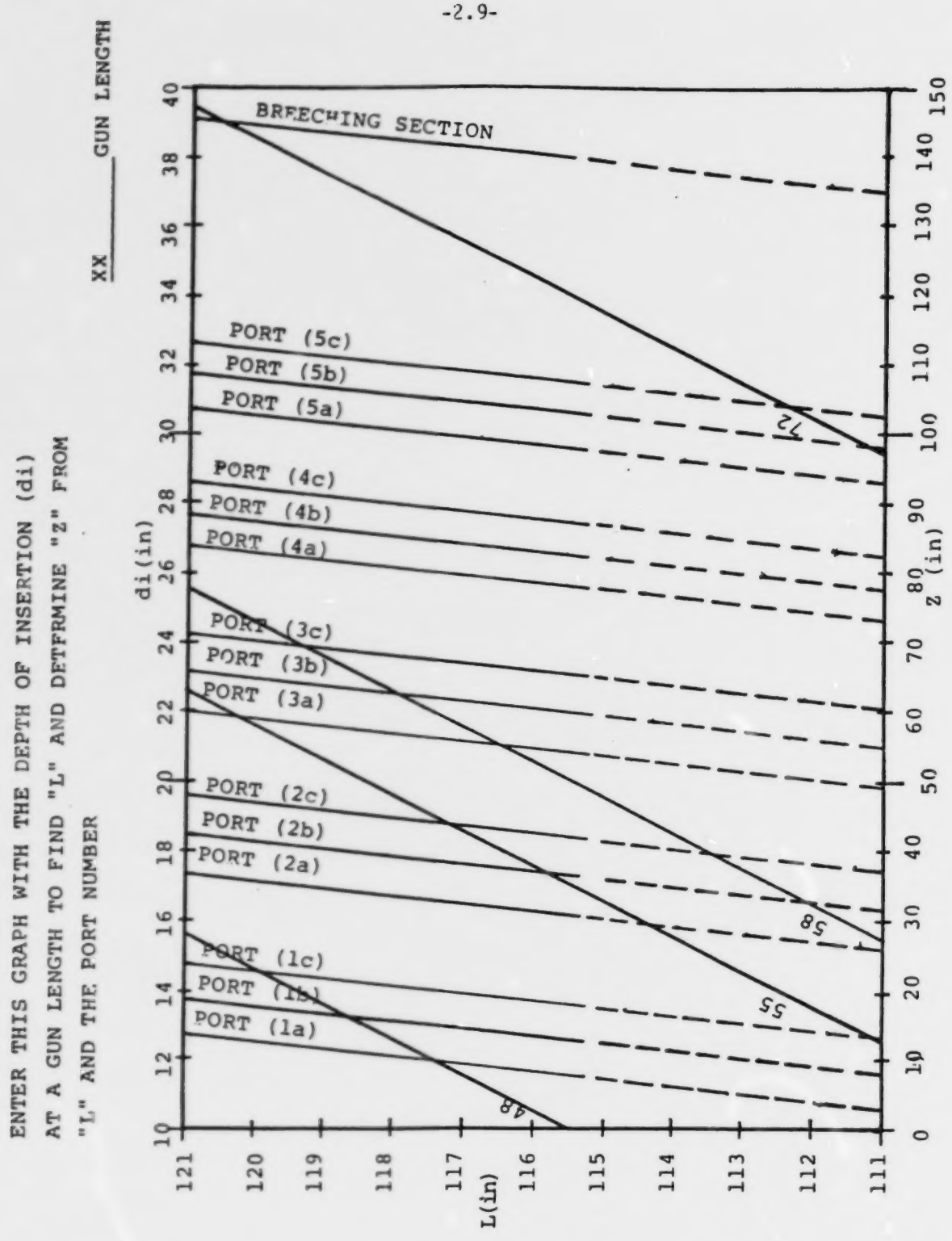


Fig 2.2: Nomograph to Calculate Dimsionless Axial Location (Z/L)

Table 2.5: Matrix of in-flame measurements for Test No. 1

Port No.	r/R						
	0	0.17	0.35	0.52	0.70	0.87	1.0
1a							+,#
b	x,o	x,o	x,o	x,o	x,o	x,o	
c							+,#
2a							+,#
b	x,o	x,o	x,o	x,o	x,o	x,o	
c							+,#
3a							+,#
b	x,o,s	x,o	x,o	x,o	x,o	x,o	
c							+,#
4a							+,#
b	x,o	x	x	x	x	x	
c							+,#
5a							+,#
b	x,o	x	x	x	x	x	
c							+,#

Legend[a]:
x Flame temperature
o Gas analysis
s Solids sampling
+ Total radiation
# Total heat flux

(a) This legend applies to Tables 2.5 to 2.9

Table 2.6: Matrix of in-flame measurements for Test No. 2

Port No.	r/R						
	0	0.17	0.35	0.52	0.70	0.87	1.0
1a							+,#
b	x,o	x,o	x,o	x,o	x,o	x	
c							+,#
2a							+,#
b	x,o	x,o	x,o	x,o	x,o	x,o	
c							+,#
3a							+,#
b	x,o,s	x	x	x	x	x	
c							+,#
4a							+,#
b	x,o	x	x	x	x	x	
c							+,#
5a							+,#
b	x,o	x	x	x	x	x	
c							+,#

Table 2.7: Matrix of in-flame measurements for Test No. 3

Port No.	r/R						
	0	0.17	0.35	0.52	0.70	0.87	1.0
1a							+,#
b	x,o,s	x,o	x,o	x,o	x,o	x,o	
c							+,#
2a							+,#
b	x,o,s	x,o	x,o	x,o	x,o	x,o	
c							+,#
3a							+,#
b	x,o,s	x,o	x,o	x,o	x,o	x,o	
c							+,#
4a							+,#
b	x,o,s	x	x	x	x	x	
c							+,#
5a							+,#
b	x,o,s	x	x	x	x	x	
c							+,#

Table 2.8: Matrix of in-flame measurements for Test No. 4

Port No.	r/R						
	0	0.17	0.35	0.52	0.70	0.87	1.0
1a							+,#
b	x,o,s	x,o	x,o	x,o	x,o	x,o	
c							+,#
2a							+,#
b	x,o,s	x,o	x,o	x,o	x,o	x,o	
c							+,#
3a							+,#
b	x,o,s	x,o	x,o	x,o	x,o	x,o	
c							+,#
4a							+,#
b	x,o,s	x	x	x	x	x	
c							+,#
5a							+,#
b	x,o,s	x	x	x	x	x	
c							+,#

Table 2.9: Matrix of in-flame measurements for Test No. 5

Port No.	r/R						
	0	0.17	0.35	0.52	0.70	0.87	1.0
1a							+,#
b	x,o	x	x,o	x	x	x	
c							+,#
2a							+,#
b	x,o,s	x	x,o	x	x,o	x	
c							+,#
3a							+,#
b	x,o	x	x,o	x,o	x,o	x	
c							+,#
4a							+,#
b	x,o,s	x	x	x	x	x	
c							+,#
5a							+,#
b	x,o	x	x	x	x	x	
c							+,#

The testing pattern outlined here was maintained throughout each series of tests. This system allows a thorough examination of the characteristics of each flame and it also gives a basis for comparing flames when any one of a number of variables is altered.

2.2.4 Analytical tests

In addition to the fuel analyses, tests of in-flame particulate and deposited ash were performed. The analytical tests were carried out according to ASTM or ISO standards and are detailed in Appendix IV.

In this report, particulate samples are coded P·X·Y where P denotes particulate; X the test number; and Y the sample number for that test. Table 2.10 summarises the particulate sample collection data. Ash samples follow a similar coding (A·X·Y) where A denotes ash. Table 2.11 summarises the ash sample collection data.

Table 2.10: Particualte sample collection data

Sample No.	Date	Time	Location (all on ℄)	Filter No.	Coal Lab Sample No.
P.1.1	Aug 9	09:04	Breeching	A12	1311
P.1.2	Aug 9	10:15	3b	A10	1310
P.2.1	Aug 10	10:42	Breeching	A9	1312
P.2.2	Aug 10	11:33	3b	A11	1313
P.3.1	July 19	09:39	Breeching	B14	1298
P.3.2	July 19	10:57	5b	B1	1291
P.3.3	July 19	11:35	4b	B15	1299
P.3.4	July 19	12:31	3b	B9	1296
P.3.5	July 19	13:12	2b	B8	1295
P.3.6	July 19	14:04	1b	B2	1292
P.4.1	July 17	15:14	Breeching	B24	1302
P.4.2	July 17	16:23	5b	B18	1301
P.4.3	July 17	17:07	4b	B16	1300
P.4.4	July 18	10:30	3b	B12	1304
P.4.5	July 18	11:34	2b	B11	1303
P.4.6	July 18	16:05	1b	B13	1305
P.5.1	July 20	01:27	Breeching	4B(≡)	1297
P.5.2	July 20	02:11	4b	B4	1294
P.5.3	July 20	02:55	2b	B3	1293

Table 2.11: Ash sample collection data

Sample	Date	Time	Location	F.T.(a) Sample #	C.L.(b) Sample #
A.3.1	07/12/84	0600	F.T. Hatch	FT34-1S	MS012
A.3.2	07/13/84	0600	Port 5	FT34-2S	MS008
A.4.1	07/17/84	0600	Port 5	FT35-1S	MS009
A.4.2	07/18/84	0600	Port 5	FT35-2S	MS010
A.4.3	07/19/84	0600	Port 5	FT35-3S	MS011

(a)F.T. = Flame Tunnel
(b)C.L. = Coal Laboratory

3. FLAME OPTIMISATION

Before commencing the optimisation process, the desired test conditions were estabished. These conditions were:

(i) a thermal input ($\dot{Q}$) of 1.8 MW;

(ii) a furnace load of 0.81 ±0.1 MW; (which corresponds to 44-46% of the thermal input, refer to Section 4.5); and

(iii) an excess of oxygen of either 3 or 5%.

The desired thermal input was established from the mass burning rate ($\dot{m}$) which is given by:

$$\dot{m} = \dot{Q}/\Delta H_c$$

where ΔH_c = net corrected calorific value of the fuel.

The initial furnace load was set by adjusting the water flowrates through the cooling jackets to the values shown in Table 3.1.

Table 3.1: Initial cooling-water flowrate settings

Water jacket section[a]	flowrate/[$dm^3 min^{-1}$]
C1	40.0 ± 5.0
C2	35.0 ± 5.0
C3	30.0 ± 5.0
C4	30.0 ± 5.0
C5	25.0 ± 5.0

(a) Section C1 is at the windbox end and section C5 is at the rear of the combustion chamber

Once the mass flowrate of fuel was established, and hence the desired thermal input, the combustion air flowrate was adjusted to give the required excess oxygen level. Continuous analysis of the flue gas, drawn from the furnace exit breeching, made with a paramagnetic oxygen analyser (Beckman Model 755) enabled the desired excess oxygen level to be controlled.

After the desired test conditions were established the procedure of flame optimisation was commenced. The optimisation process involved adjustment of two main sets of parameters. These were:

(i) adjustments which affect the flame stability; and

(ii) adjustments to the burner nozzle which affect the quality of atomisation.

Flame stability is affected by adjustment of three main parameters; namely:

(i) the position of the burner gun within the refractory throat;

(ii) the combustion air swirl settings; and

(iii) the cooling air pressure and flowrate to the burner gun.

The position of the gun within the burner throat and the degree of combustion air swirl are interactive parameters. The gun was positioned to ensure no impingement of the fuel spray on the divergent refractory throat. The combustion air swirl was then adjusted to achieve minimum rotation of the flame, whilst avoiding impingement of the spray and maximising the recirculated mass flux, consistent with flame stability. The cooling air flowrate and pressure was then adjusted to ensure adequate cooling of the burner nozzle without affecting flame stability.

Inspection of the flame through access ports along the combustion chamber enabled visual optimisation to produce the shortest flame with a minimum number of sparklers.

3.1 Burner nozzle and gun assembly

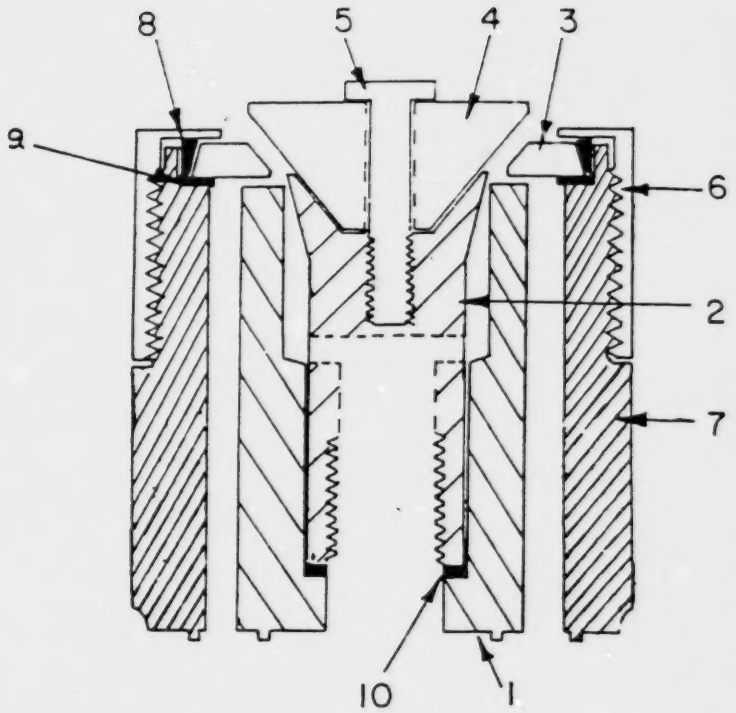
The National Research Council of Canada (NRCC) became involved in a coal-liquid mixtures burner tip development program late in 1981[10]. Subsequently this has grown into a larger, overall program, on CLM.

Expertise in ceramics, developed at the Atlantic Research Laboratories (ARL) of NRCC, has been employed in the nozzle design to overcome erosion problems. Figure 3.1 shows the basic components of the burner nozzle. The wear ring (part No. 3) and the deflector cone (part No. 4) are made of alumina. Altering the size of the shim for adjustment of the atomising medium clearance (part No. 10) also changes the final gap between the cone and wear ring. Hence a second shim (part No. 9) allows independent adjustment of the fuel clearance.

The burner nozzle screws directly onto the end of the burner gun assembly which is shown in Fig 3.2. The burner gun is equipped with a steam fuel preheater and thermocouple which enables fine control of the fuel temperature.

3.2 Aerodynamic effects

A swirling combustion air flow affects the flame stability and combustion intensity of pressure jet oil flames. When the momemtum of the air flow is high, the variation of the oil spray angle has no significant influence on the flame properties. Experimental tests at IFRF at IJmiuden[11] found that when the mean axial velocity of the combustion air was low ($10 ms^{-1}$) the degree of swirl needed for flame stabilisation often had an adverse effect on combustion efficiency. This was because the swirling air jet had too wide an angle of spread, directing the air outwards and separating it from the fuel-rich zone of the jet. This process impairs mixing and causes incomplete combustion.



1. NOZZLE BASE
2. ATOMIZING MEDIA DISTRIBUTOR
3. WEAR RING
4. DEFLECTOR CONE
5. DEFLECTOR CONE PIN-DOWN
6. CAP NUT
7. NOZZLE BASE EXTENSION
8. WEAR RING LOCATION RING
9. WEAR RING ADJUSTMENT SHIMS
10. ATOMIZING MEDIA DISTRIBUTOR ADJUSTMENT SHIMS

Fig. 3.1: NRCC Variable Geometry CLM Nozzle

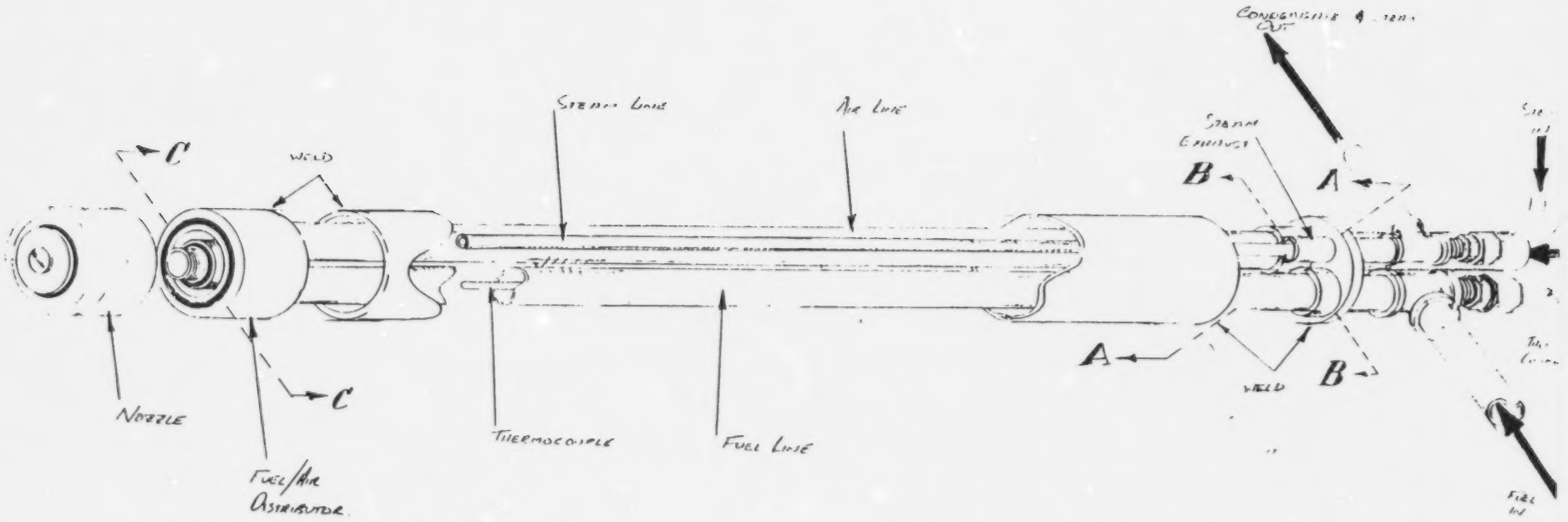


Fig. 3.2: NRCC Burner Gun Assembly

It was also found that when the mean axial velocity of the combustion air was increased to 30ms^{-1} moderate swirl was needed to stabilise the flame at the burner and mixing was greatly improved. When the air velocity was increased to 50ms^{-1} the flame could not be stabilised at the burner.

Detailed aerodynamic investigations of swirling annular jets has shown that hot combustion products are recirculated within the central recirculation zone and pass through the oil spray, forming a flame front as shown in Fig 3.3.(11) Small droplets are also carried into the central hollow cone to form a "laminarised" pilot flame.

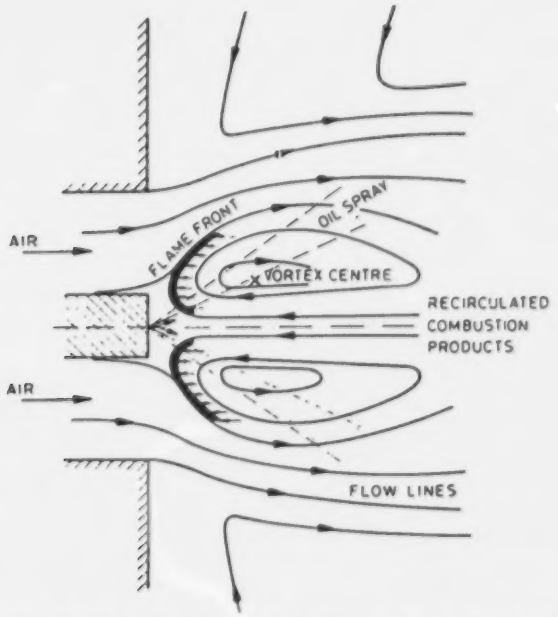


Fig. 3.3: Stabilization of a Pressure Jet Oil Flame by Internal Recirculation (after ref 11)

The shape of the burner throat exit strongly affects the flow pattern of swirling jets. In particular, the use of a divergent burner throat geometry causes two main effects. These are:

(i) there is an increase in the radial distance of separation between peaks of axial and tangential velocities; and

(ii) there is an increase in the recirculated mass flowrate.

It has been found that the optimum half angle of divergence is about 35° and that $1.0 \leq L''/D \leq 2.0$ gives the most stable conditions, where L'' is the axial length of the divergent section and D is the throat diameter before the divergent section (see Fig 3.7).

Investigations of burner throat geometry and the interaction with swirling flows has identified three basic flow types[11]. Two will be discussed here: types A and B shown in Fig 3.4.

Type A With little or no swirl, the annular air flow tends to separate from the nozzle surface near the burner throat. Flames produced with this type of flow have a fluctuating flame front positioned downstream from the burner exit.

Type B With moderate or high swirl, the air flow is stably attached to the divergent burner throat and encloses a large toroidal vortex reverse flow region within the centre of the jet. In general, this is the desired flow pattern which produces very stable flames with ignition close to the burner nozzle or inside the divergent burner throat.

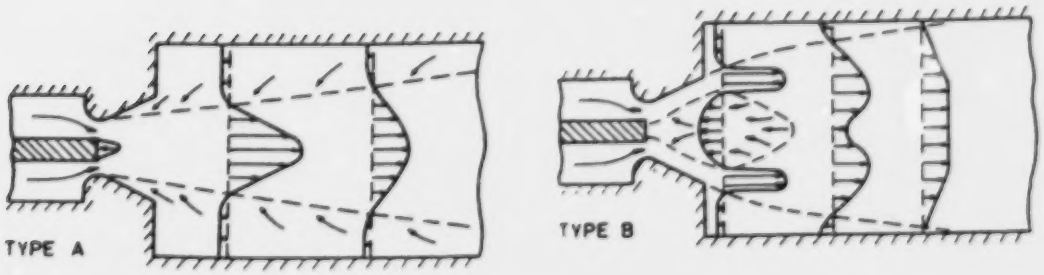


Fig. 3.4: Flow Types for Swirling Jets and Flames Issuing from a Divergent Burner Throat (after ref 11)

The relative stability between flow types A and B as a function of the Swirl Number (S) and the position of the burner gun within the throat is shown in Fig 3.5 The value of the critical swirl number (the minimum swirl required for establishing a type B flow pattern) is a function of the half angle of the divergent burner throat as shown in Fig 3.6.

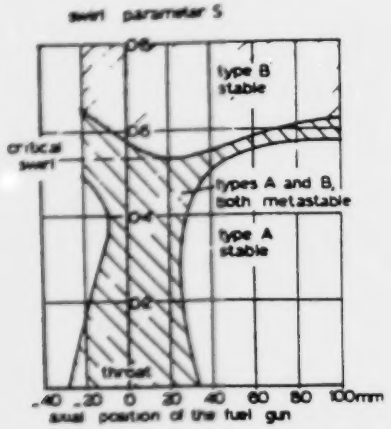

swirl parameter S
type B stable
critical swirl
types A and B, both metastable
type A stable
throat
-40 -20 0 20 40 60 80 100mm
axial position of the fuel gun

Fig. 3.5: Relative Stability for Flow Types A and B in a Divergent Burner Throat with a Half Angle (α) of 35° (after ref 11)

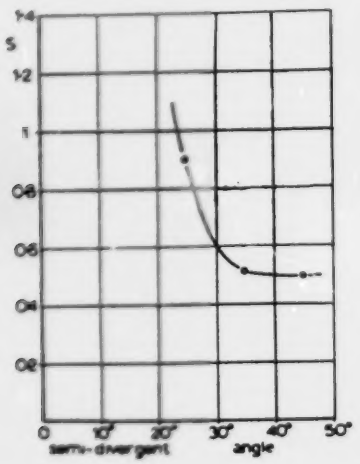


Fig. 3.6: Critical Swirl as a Function of the Half Angle of Divergence (after ref 11)

3.3 Optimisation process

The CES flame tunnel is fitted with a Babcock-Duiker 200 swirl register manufactured by MBB Mechanical Services Ltd. It is of the 100% swirl type. The combustion air is divided into two streams. Approximately 90% of the air is directed through the air foil swirl vanes (secondary air). Primary air enters through adjustable concentric openings in the front plate of the register and is swirled (in a direction opposite to the secondary swirler) by fixed swirl vanes set in a convergent discharge cone. The primary and secondary swirl settings are adjusted by means of levers positioned at the front of the windbox.

The original burner throat geometry is shown in Fig 3.7. The entire throat and front wall of the combustion chamber was cast in a high temperature refractory material.

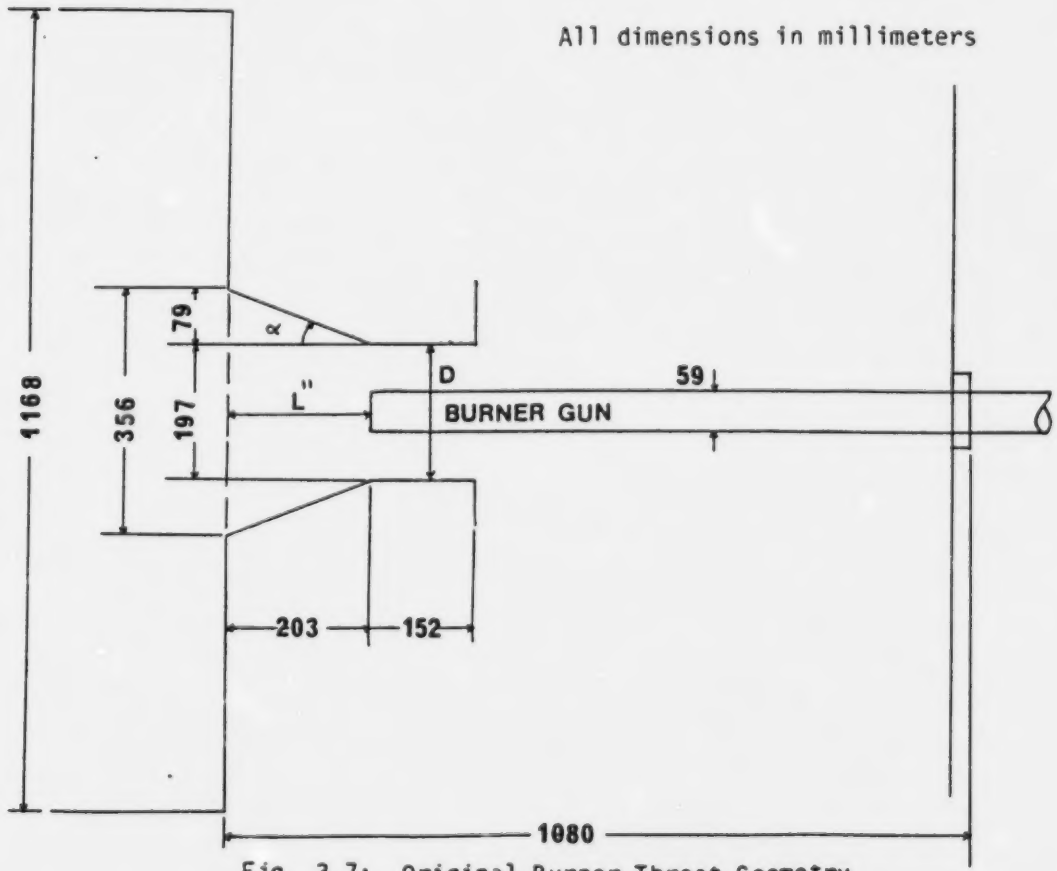


Fig. 3.7: Original Burner Throat Geometry

The optimisation process commenced in March, 1984. To facilitate discussion of the entire optimisation process the flame types will be designated PT1 to PT8 (pretest number)(a). Table 3.2 summarises the conditions for all the pretest flames. Table 3.3 gives the coordinates of positions at which flow boundary reversals were detected in each pretest flame.

Table 3.2: Pretest flame conditions(a)

Pretest No.	Fuel	Swirl Prim/sec	Gun Pos'n(b) /[mm]	Throat geometry	Swirl register	Spray angle /[°]	Distance(c) /[mm]
PT1	HFO	0/4	-51	original	original	80	3070
PT2	HFO	5/4	+32	original	original	80	3020
PT3	CW	0/4	+76	original	modified	80	2950
PT4	CW	3/4	+76	original	modified	80	2950
PT5	CW	5/4	+76	original	modified	60	2950
PT6	CW	5/4	+76	original	modified	60	2950
PT7	CW	5/4	- 6	modified	modified	60	3050
PT8	CW	2/4	- 6	modified	modified	50	3050

Table 3.3: Flow boundary coordinates for pretest flames

	PT1		PT2		PT3		PT4	
Port No.	Z/L	r/R	Z/L	r/R	Z/L	r/R	Z/L	r/R
1a	0.11	0.41	0.09	0.46	0.07	0.28	0.07	--
b	0.15	0.52	0.13	--	0.11	0.33	0.11	0.22
c	0.20	0.52	0.18	0.28	0.16	0.43	0.16	0.30
2a	0.31	0.61	0.29	0.26	0.28	0.39	0.28	0.46
b	0.35	0.70	0.34	0.24	0.32	0.30	0.32	0.39
c	0.40	0.37	0.39	0.26	0.37	0.09	0.37	0.22
3a	0.50	--	0.49	--	0.47	--	0.47	--

	PT5		PT6		PT7		PT8	
Port No.	Z/L	r/R	Z/L	r/R	Z/L	r/R	Z/L	r/R
1a	0.07	0.26	0.07	0.24	0.07	0.30	0.07	0.41
b	0.11	0.48	0.11	0.50	0.11	0.59	0.11	0.54
c	0.16	0.50	0.16	0.63	0.16	0.48	0.16	0.57
2a	0.28	0.46	0.28	0.48	0.28	0.35	0.28	0.52
b	0.32	0.26	0.32	0.41	0.32	0.39	0.32	0.43
c	0.37	--	0.37	0.30	0.37	--	0.37	0.39
3a	0.47	--	0.47	--	0.47	--	0.47	--

(a) 1. All pretests were carried out with a 3 percent excess oxygen level as measured in the breeching.
2. All pretests used air as the atomisation medium excect PT6 in which steam was used.

(b) Atomiser position relative to the beginning of the divergent section in the burnber throat: + indicates downstream and - indicates upstream from this reference point.

(c) Distance from atomiser to breeching of the flame tunnel.

Figure 3.8 shows the flow boundary for flame PT1. This represents the most stable flame possible under these conditions. All the combustion air passed through the air foil swirl vanes. As can be seen from Fig 3.8, a type B flow pattern was established with the spray pattern completely missing the recirculation zone. The flame front was unstable exhibiting a persistent fuel spray which impinged on the furnace walls causing coke build-up with a large number of sparklers. Any attempts to increase the degree of swirl resulted in an asymmetric flame shape. Figure 3.8 also shows that the burner gun was pulled back into the throat as far as possible: in fact the oil spray began to impinge on the refractory throat.

Figure 3.9 shows the flow boundary for flame PT2. The conditions were the same as for flame PT1 except that primary air was directed through the fixed swirl blades. An extremely unstable flame resulted. This was because the fixed swirl blades imparted swirl to the primary air in the opposite direction to that of the secondary air.(a) The constriction in the flow boundary suggests that the conterswirl in the primary air destroys the internal recirculation zone.

As a result of discussions with the Scientific Authority it was decided to remove the fixed swirl blades in order to avoid conterswirling when passing primary air through the register. The fixed swirl blades were removed on 23 May 1984. In Table 3.2 the modified swirl register refers to after these blades were removed.

Figures 3.10 and 3.11 show the flow boundaries for flames PT3 and PT4 respectively. Both were CW flames. Identical conditions were maintained for both flames except for the degree of swirl. With flame PT3 all the air passed through the air foil swirl vanes, whereas with flame PT4 some primary air was

(a) In this context primary and secondary air refers to the air which passes through the fixed swirl blades and the air foil swirl vanes respectively.

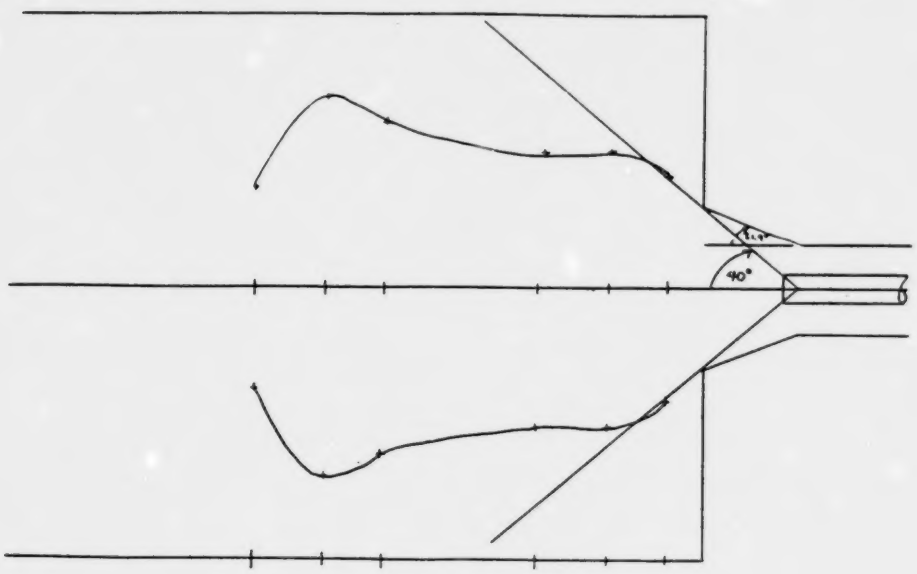


Fig. 3.8: Flow Boundary for Flame PT1

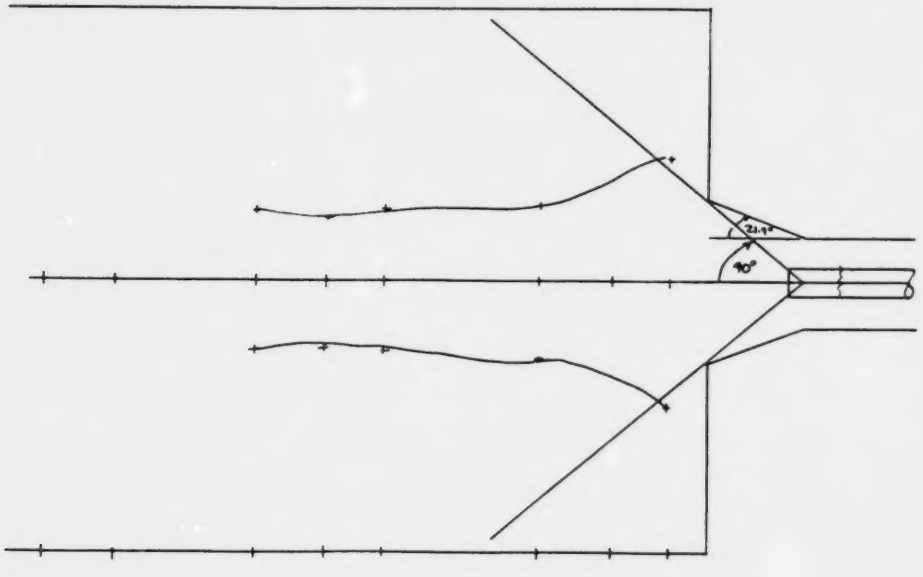


Fig. 3.9: Flow Boundary for Flame PT2

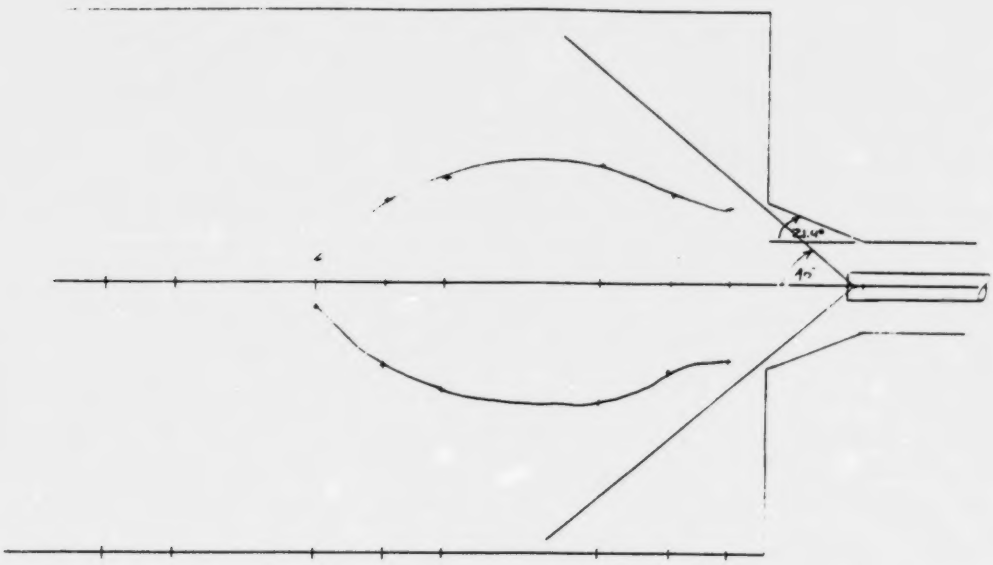


Fig. 3.10: Flow Boundary for Flame PT3

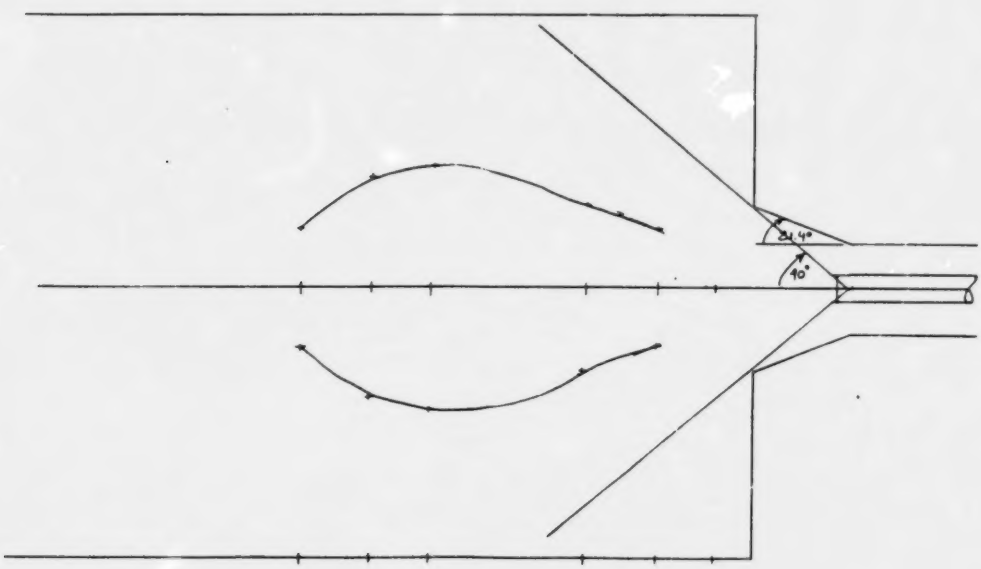


Fig. 3.11: Flow Boundary for Flame PT4

admitted. The effect of primary air is to reduce the degree of swirl. Figures 3.10 and 3.11 show type B flames. The increase in primary air moved the internal recirculation zone further downstream away from the fuel spray. In both cases the burner gun was as far back into the throat as possible.

For flames PT1 to PT4 the nozzle spray angle was 80°. After discussion with the Scientific Authority and NRCC, it was decided that this spray angle was too wide and so new components were made available by NRCC to give a 60° spray angle.

On 30 May, 1984, flames PT5 and PT6 were tested. The flow boundaries for these flames are shown in Figs 3.12 and 3.13. The flame conditions were identical except that flame PT5 was air atomised and flame PT6 was steam atomised. The reduction in nozzle spray angle made a vast improvement. The flames were type B but the recirculation zone was not large enough to cause fuel ignition near the atomiser.

Further discussion with the Scientific Authority led to the decision to alter the burner throat geometry. All the tests were to be carried out with the maximum air preheat possible. Thus, the combustion air temperature was about 288°C. The increase in temperature of the air meant that the mean axial velocity would be higher than at ambient conditions. The new burner throat geometry is shown in Fig 3.14 Two major changes were proposed; namely:

(1) an increase in the throat diamater; and

(2) a change in the half angle of divergence.

The effect of increasing the diameter was to reduce the mean axial velocity to not greater than 35 ms-1. The increase in the half angle of divergence to 35° was to reduce the critical swirl number so that type B flames could be established. Figure 3.6 shows that increasing the half angle of divergence from 21.4°C to 35° reduces the critical swirl number drastically.

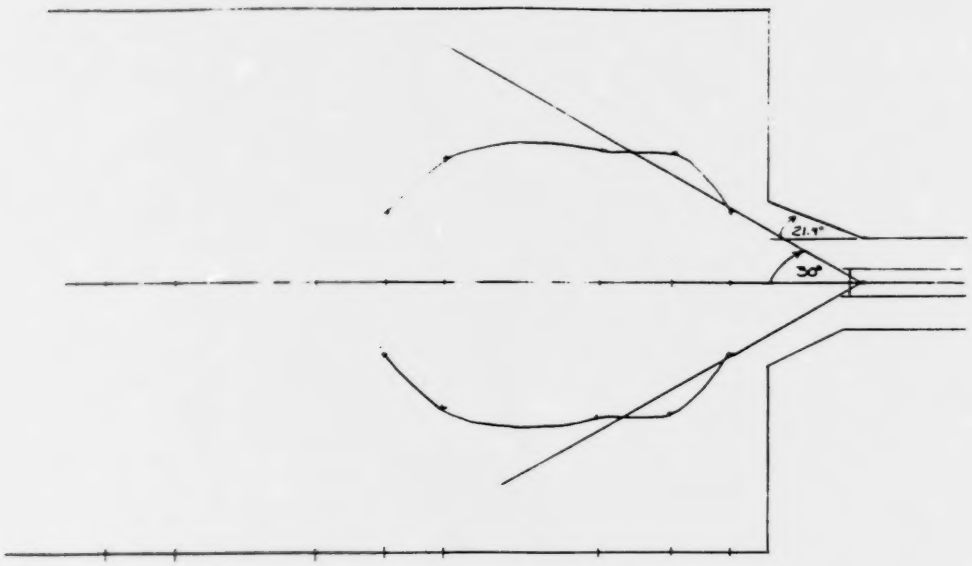


Fig. 3.12: Flow Boundary for Flame PT5

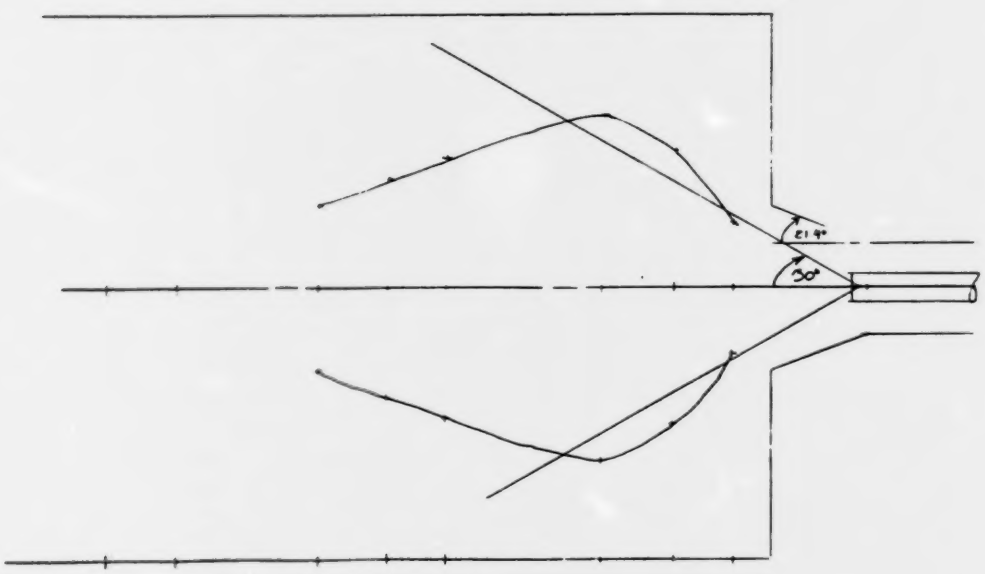
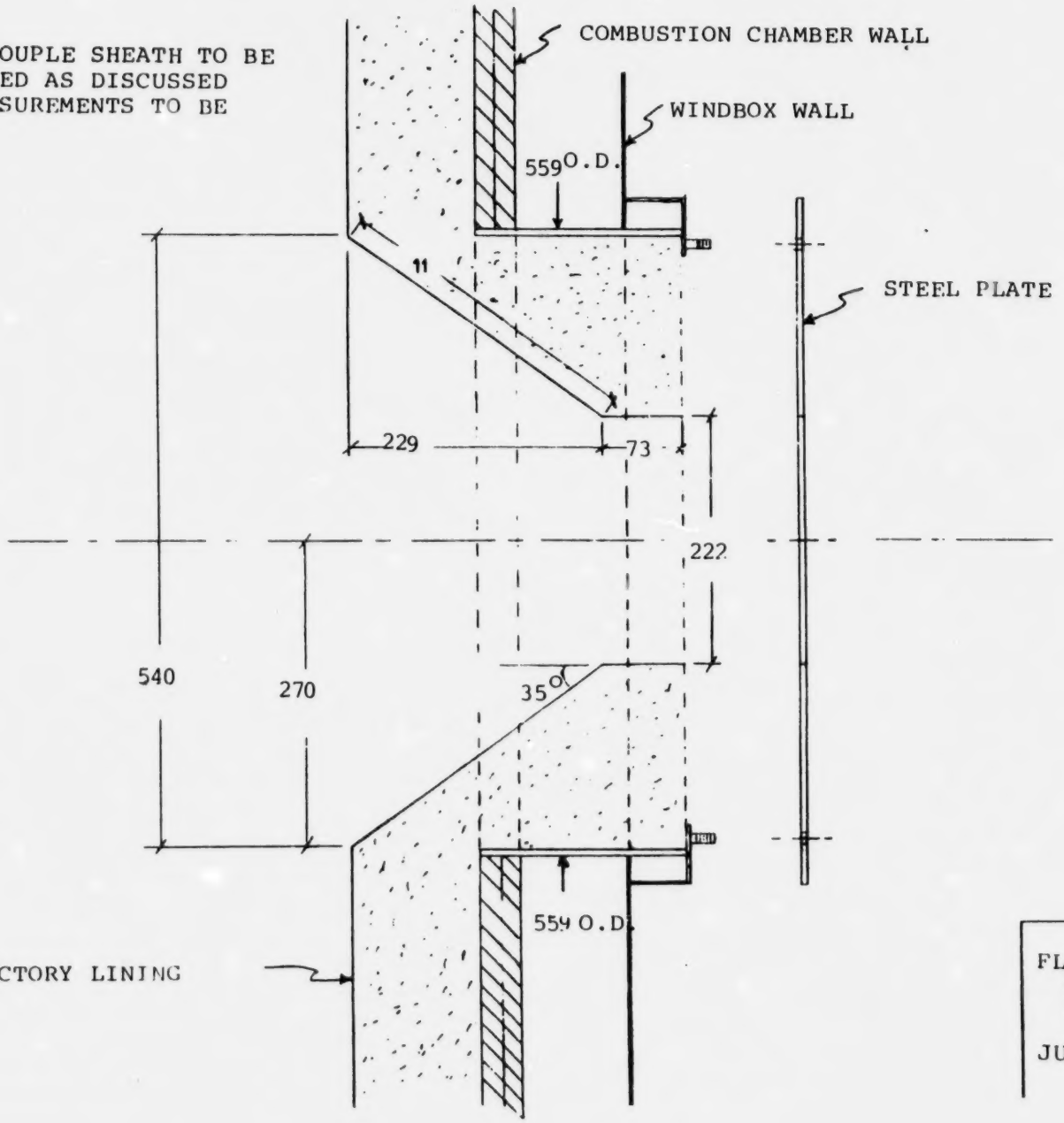


Fig. 3.13: Flow Boundary for Flame PT6

NOTES:
1. THERMOCOUPLE SHEATH TO BE INSTALLED AS DISCUSSED
2. ALL MEASUREMENTS TO BE ± 3 mm



FLAME TUNNEL
BURNER THROAT
DESIGN
JUNE 8/84

Fig. 3.14: Modified Burner Throat Geometry

The modified burner throat was installed in early June.

Figure 3.15 shows the flow boundary map for flame PT7. A 60° spray angle was used firing CW. Much lower swirl was needed and a type B flame was readily established. However, inspection of Figs 3.3 and 3.15 show that the fuel spray does not pass through the boundary. With HFO, however, entirely satisfactory results were obtained. For CW the nozzle spray angle was reduced to 50° and an excellent, stable, type B flame resulted as shown in Fig 3.16. It appears that the improvement was caused by the increase in the recirculation flow resulting from the wider quarl angle.

The optimum conditions for the atomiser, swirl register and the quarl design used in this study are summarised respectively as follows:

1) HFO : 60° spray angle - modified swirl register - 35° half angle

2) CW : 50° spray angle - modified swirl register - 35° half angle.

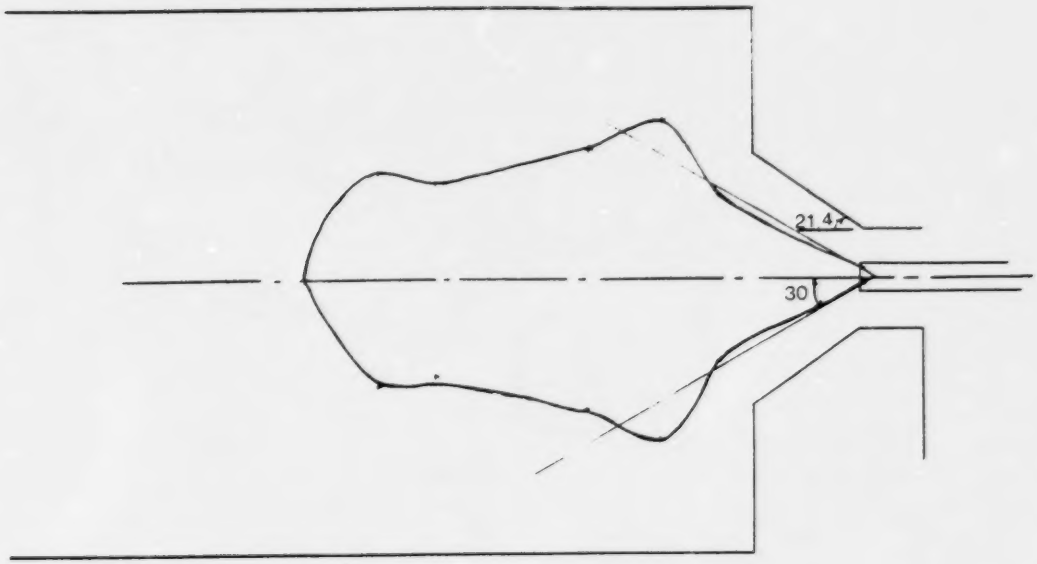


Fig. 3.15: Flow Boundary for Flame PT7

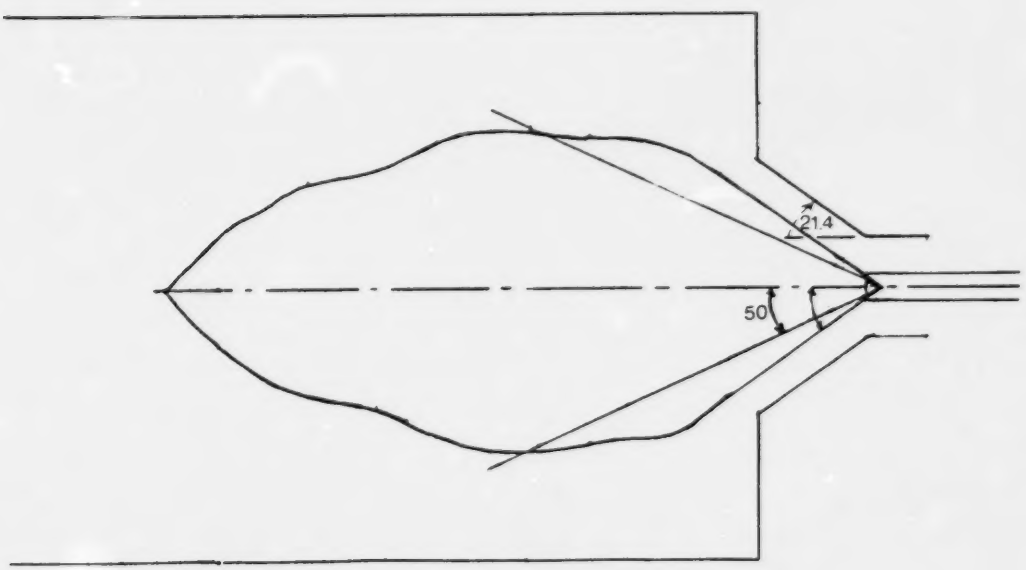


Fig. 3.16: Flow Boundary for Flame PT8

3.4 Steady state operating condtions

Once optimised flames had been established for both HFO and CW, stable operating conditions for each test, 1 through 5, are summarised in Tables 3.4 to 3.8

Table 3.4: Average operating parameters for Test 1

fuel temperature at burner gun	377 ± 1 K
fuel pressure at burner gun	539 ± 10 kPa
fuel mass flowrate	0.0416 ± 0.0 kgs^{-1}
thermal input	1.8 MW
atomisation air pressure at burner gun	721 ± 2 kPa
atomisation air flowrate	889 ± 0.0 dm^3min^{-1}
combustion air flowrate	39351 ± 849 dm^3min^{-1}
combustion air temperature	510 ± 12 K
atomisation air/fuel mass ratio	0.42
excess O_2	5%
combustion air O_2	19.6%
position of nozzle in throat[a]	-25 mm

[a]Atomiser position relative to the beginning of the divergent section in the burner throat: + indicates downstream and - indicates upstream from this reference point. This note applies for tables 3.4 to 3.8.

Table 3.5: Average operating parameters for Test 2

fuel temperature at burner gun	377 ± 1	K
fuel pressure at burner gun	482 ± 6	kPa
fuel mass flowrate	0.0416 ± 0	kgs^{-1}
thermal input	1.8 MW	
atomisation steam pressure at burner gun	722 ± 0	kPa
atomisation steam flowrate	0.017 ± 0	kgs^{-1}
combustion air flowrate	40625 ± 0	dm^3min^{-1}
combustion air temperature	526 ± 25	K
atomisation steam/fuel mass ratio	0.41	
excess O_2	5%	
combustion air O_2	19.6%	
position of nozzle in throat	-25 mm	

Table 3.6: Average operating parameters for Test 3

fuel temperature at burner gun	301 ± 5	K
fuel pressure at burner gun	539 ± 26	kPa
fuel mass flowrate	0.073 ± 0	kgs^{-1}
thermal input	1.8 MW	
atomisation air pressure at burner gun	757 ± 6	kPa
atomisation air flowrate	1234 ± 0	dm^3min^{-1}
combustion air flowrate	33972 ± 1982	dm^3min^{-1}
combustion air temperature	539 ± 22	K
atomisation air/fuel mass ratio	0.34	
excess O_2	3%	
combustion air O_2	19.6%	
position of nozzle in throat	+9.5 mm	

Table 3.7: Average operating parameters for Test 4

fuel temperature at burner gun	304 ± 3	K
fuel pressure at burner gun	549 ± 27	kPa
fuel mass flowrate	0.073 ± 0	kgs^{-1}
thermal input	1.8 MW	
atomisation air pressure at burner gun	754 ± 4	kPa
atomisation air flowrate	1200 ± 0	dm^3min^{-1}
combustion air flowrate	42465 ± 283	dm^3min^{-1}
combustion air temperature	526 ± 12	K
atomisation air/fuel mass ratio	0.33	
excess O_2	5%	
combustion air O_2	19.6%	
position of nozzle in throat	+9.5 mm	

Table 3.8: Average operating parameters for Test 5

fuel temperature at burner gun	303 ± 3.2	K
fuel pressure at burner gun	413 ± 19	kPa
fuel mass flowrate	0.073 ± 0.0	kgs^{-1}
thermal input	1.8 MW	
atomisation steam pressure at burner gun	696 ± 17	kPa
atomisation steam flowrate	0.017 ± 0.0	kgs^{-1}
combustion air flowrate	41616 ± 1416	dm^3min^{-1}
combustion air temperature	527 ± 27	K
atomisation steam/fuel mass ratio	0.23	
excess O_2	5%	
combustion air O_2	19.6%	
position of nozzle in throat	+9.5 mm	

4. RESULTS

The results of each of the measurements made during testing are presented in tabular and graphical form and appear in their respective subsections. In the graphical form, measurements plotted along the radius will have the abscissa marked as R/R /[-]. This is a computer generated title which is synonomous with the CES title r/R /[-].

4.1 Flow Boundaries

The flow boundary maps from each of the five tests are presented in Figs 4.1 to 4.5. The coordinates of each point measured on the flow boundary maps are given in Table 4.0. Radial traverses using both the Hubbard probe for HFO and the oxy-acetleyne probe for CW were made to determine the recirculation zones. The measurements were made in ports 1a through 3c.

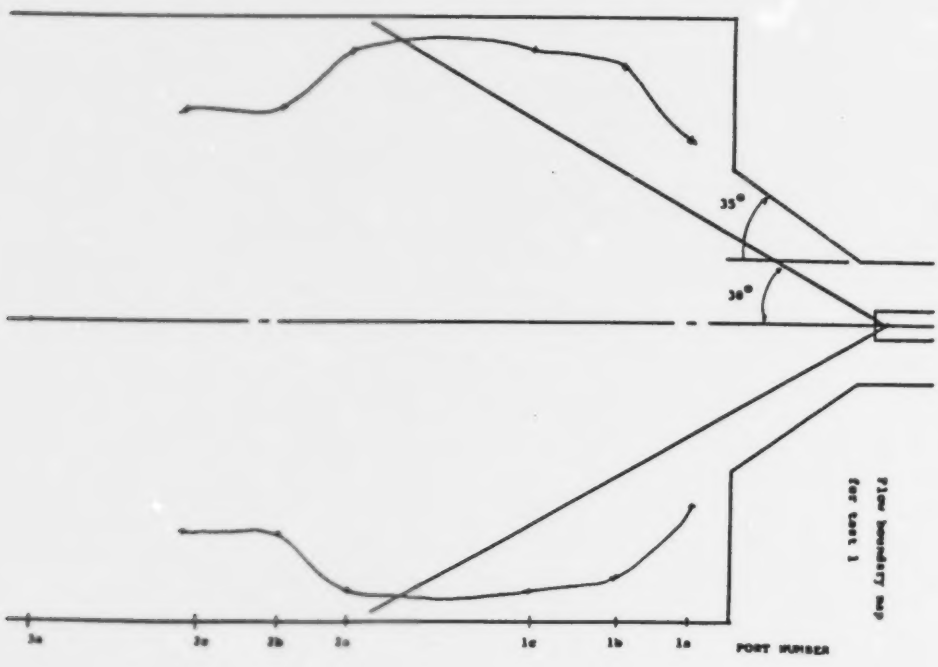


Fig. 4.1: Flow Boundary for Test 1

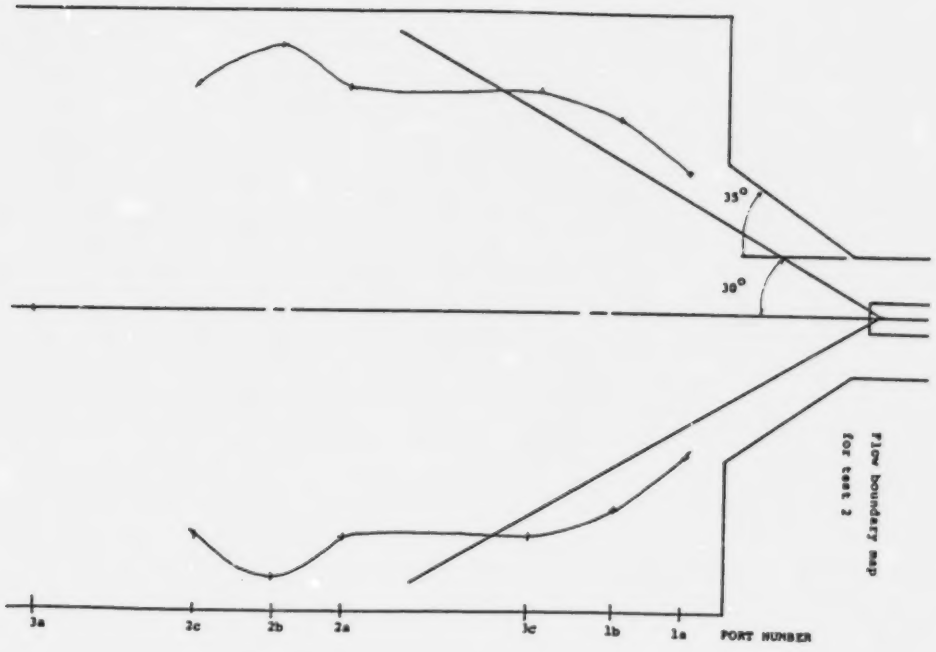


Fig. 4.2: Flow Boundary for Test 2

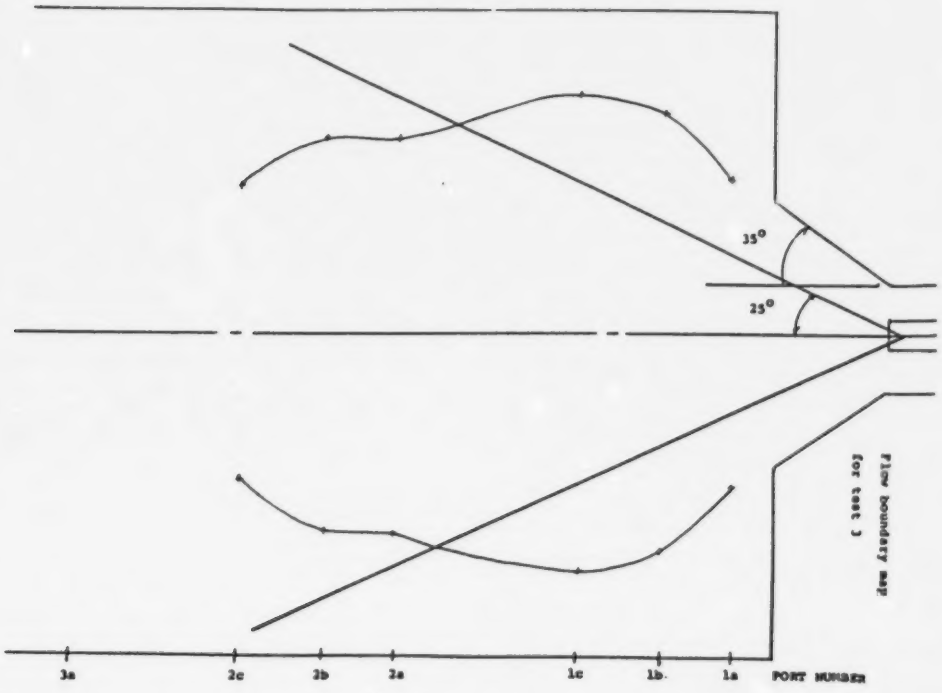


Fig. 4.3: Flow Boundary for Test 3

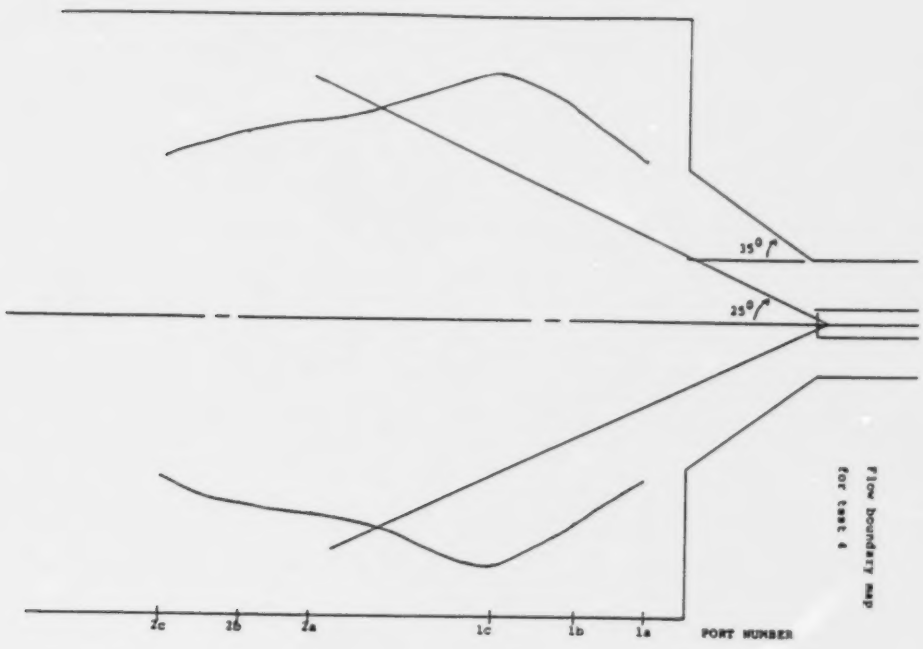


Fig. 4.4: Flow Boundary for Test 4

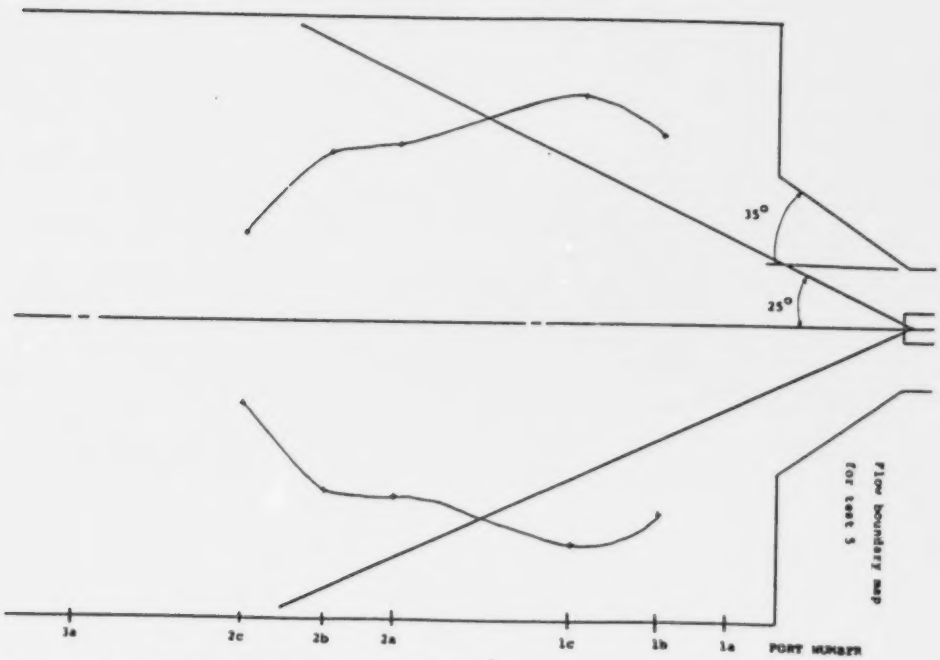


Fig. 4.5: Flow Boundary for Test 5

Table 4.0 Flow boundary coordinates for test flames

Port No.	TEST 1		TEST 2		TEST 3		TEST 4		TEST 5	
	Z/L	r/R	Z/L	r/R	Z/L	r/R	Z/L	r/R	Z/L	r/R
1a	0.13	0.57	0.13	0.43	0.12	0.47	0.12	0.50	0.12	--
b	0.17	0.78	0.17	0.61	0.17	0.67	0.17	0.63	0.17	0.63
c	0.22	0.83	0.22	0.70	0.21	0.74	0.21	0.76	0.21	0.71
2a	0.32	0.83	0.32	0.70	0.31	0.61	0.31	0.61	0.31	0.54
b	0.36	0.65	0.36	0.83	0.35	0.61	0.35	0.58	0.35	0.52
c	0.41	0.65	0.41	0.70	0.40	0.46	0.40	0.50	0.40	0.26
3a	0.51	--	0.51	--	0.50	--	0.50	--	0.50	--

4.2 Flame temperature profiles

The measured flame temperatures are presented in Tables 4.1 to 4.5 for each of the five tests performed. Figures 4.6 to 4.10 show the axial variation in centreline flame temperatures. Figures 4.11 to 4.15 show the radial variation of flame temperature at different axial locations.

Table 4.1 FLAME TEMPERATURE FOR TEST NO. 1

Temperature /[°C(K)]

Z/L \ r/R	0	0.17	0.35	0.52	0.70	0.87
0.17	1431 (1704)	1448 (1721)	1446 (1719)	1453 (1726)	1344 (1617)	1300 (1573)
0.36	1185 (1458)	1190 (1463)	1214 (1487)	1261 (1534)	1296 (1569)	1286 (1559)
0.56	1136 (1409)	1139 (1412)	1162 (1435)	1159 (1432)	1208 (1481)	1122 (1395)
0.75	1077 (1350)	1063 (1336)	1070 (1343)	1076 (1349)	1054 (1327)	964 (1237)
0.90	1061 (1334)	1036 (1309)	1025 (1298)	981 (1254)	885 (1158)	829 (1102)
1.13	(1004) 1277					

Table 4.2 FLAME TEMPERATURE FOR TEST NO.2

Temperature /[°C(K)]

Z/L \ r/R	0	0.17	0.35	0.52	0.70	0.87
0.17	1380 (1653)	1393 (1666)	1400 (1673)	1415 (1688)	1289 (1652)	1223 (1496)
0.36	1172 (1445)	1178 (1451)	1224 (1497)	1287 (1560)	1314 (1587)	1294 (1567)
0.56	1125 (1398)	1104 (1377)	1116 (1389)	1125 (1398)	1154 (1427)	1107 (1350)
0.74	1033 (1306)	1028 (1301)	1027 (1300)	1034 (1307)	1004 (1277)	859 (1132)
0.90	1019 (1292)	1008 (1281)	999 (1272)	997 (1270)	900 (1173)	770 (1043)
1.13	998 (1261)					

Table 4.3 FLAME TEMPERATURE FOR TEST NO. 3

Temperature /[°C(K)]

Z/L \ r/R	0.	0.17	0.35	0.52	0.70	0.87
0.17	1371 (1644)	1376 (1649)	1384 (1657)	1404 (1677)	1164 (1437)	1090 (1363)
0.35	1265 (1538)	1299 (1572)	1307 (1580)	1316 (1589)	1240 (1513)	1128 (1401)
0.53	1218 (1491)	1213 (1496)	1223 (1496)	1236 (1509)	1207 (1480)	1067 (1340)
0.73	1153 (1426)	1137 (1410)	1147 (1420)	1123 (1396)	1123 (1396)	1170 (1443)
0.89	1084 (1357)	1132 (1405)	1137 (1410)	1103 (1376)	1164 (1337)	897 (1170)
1.21	972 (1245)					

Table 4.4 FLAME TEMPERATURE FOR TEST NO. 4

Temperature /[°C(K)]

Z/L \ r/R	0.	0.17	0.35	0.52	0.70	0.87
0.17	1217 (1490)	1270 (1543)	1409 (1682)	1316 (1589)	1027 (1300)	927 (1200)
0.35	1191 (1464)	1210 (1483)	1235 (1508)	1229 (1502)	1211 (1484)	1160 (1433)
0.53	1141 (1414)	1151 (1425)	1168 (1441)	1175 (1448)	1230 (1503)	1206 (1479)
0.73	1120 (1393)	1140 (1413)	1169 (1442)	1190 (1463)	1177 (1450)	1081 (1354)
0.89	1181 (1391)	1110 (1383)	1124 (1397)	1121 (1394)	1077 (1350)	1028 (1301)
1.21	1052 (1325)					

Table 4.5 FLAME TEMPERATURE FOR TEST NO. 5

Temperature /[°C(K)]

Z/L \ r/R	0	0.17	0.35	0.52	0.70	0.87
0.17	1105 (1378)	1144 (1417)	1253 (1526)	1239 (1512)	1076 (1349)	1066 (1339)
0.35	1130 (1403)	1186 (1459)	1221 (1494)	1296 (1596)	1313 (1586)	1198 (1474)
0.53	1098 (1371)	1114 (1387)	1167 (1440)	1202 (1475)	1193 (1466)	1120 (1393)
0.73	1013 (1286)	1020 (1293)	1093 (1367)	1111 (1384)	1116 (1389)	1040 (1313)
0.89	1067 (1340)	1055 (1328)	1096 (1369)	1091 (1364)	1072 (1345)	1032 (1305)
1.21	1037 (1310)					

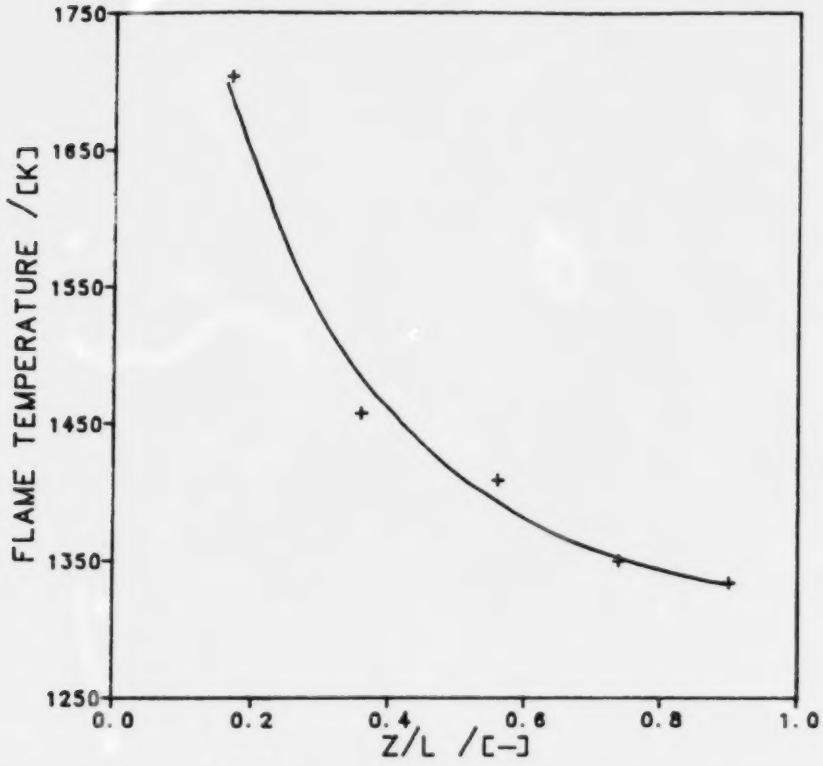


Fig. 4.6: Axial Temperature Profile for Test 1

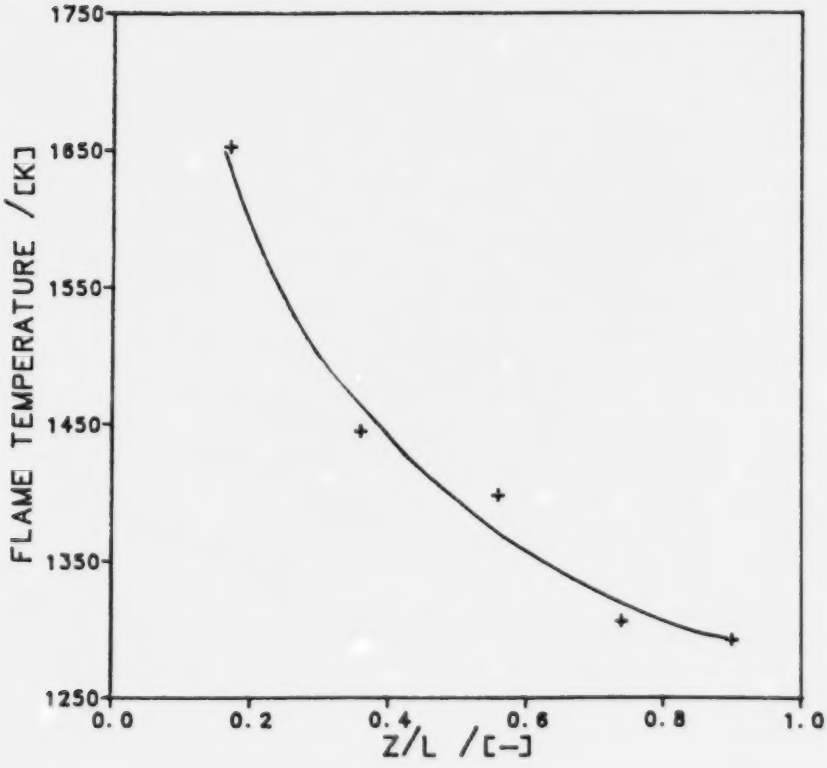


Fig. 4.7: Axial Temperature Profile for Test 2

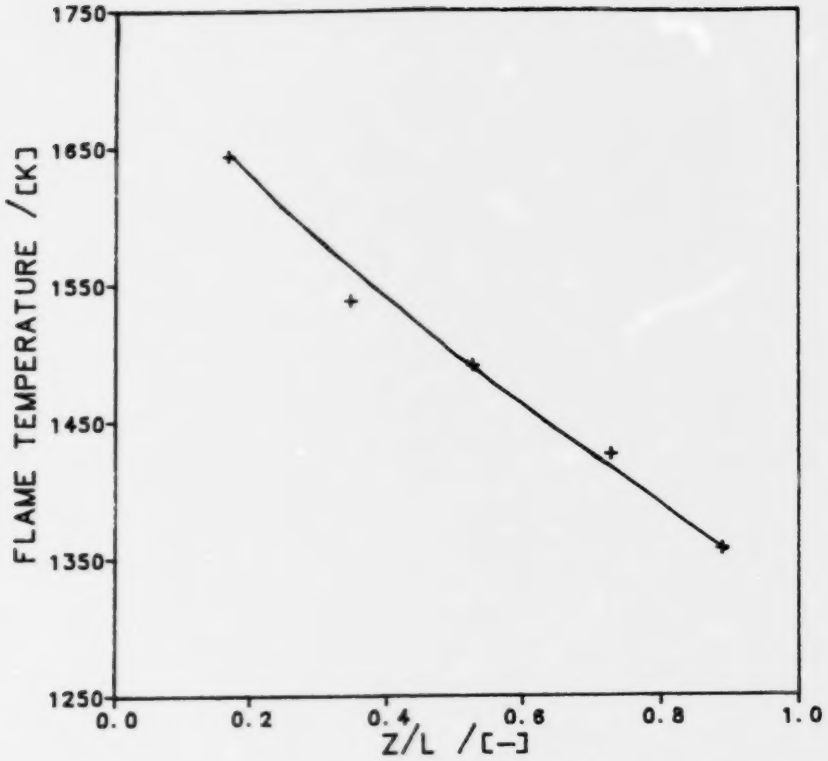


Fig. 4.8: Axial Temperature Profile for Test 3

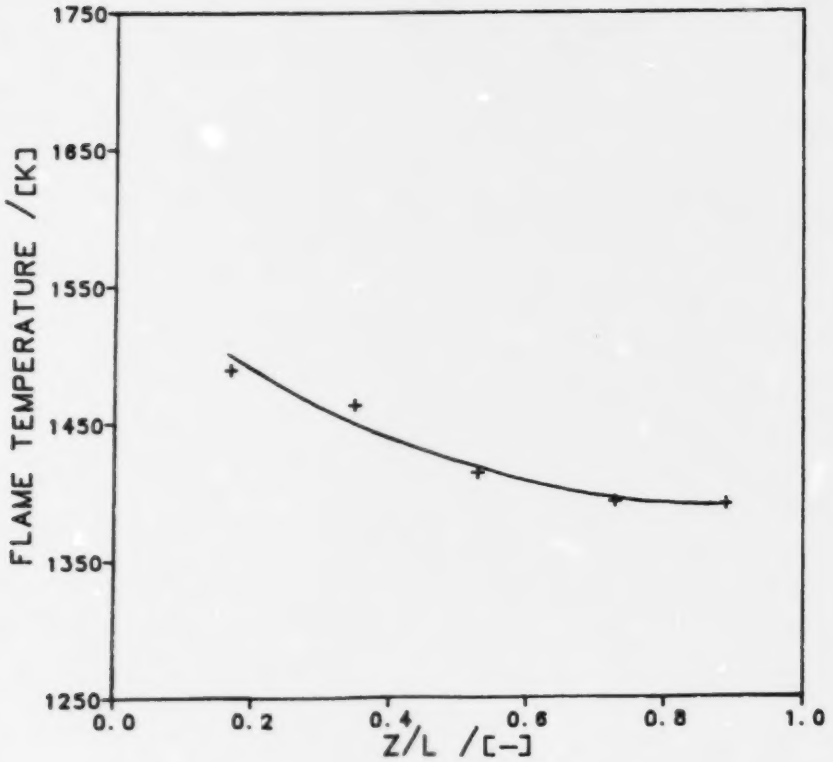


Fig. 4.9: Axial Temperature Profile for Test 4

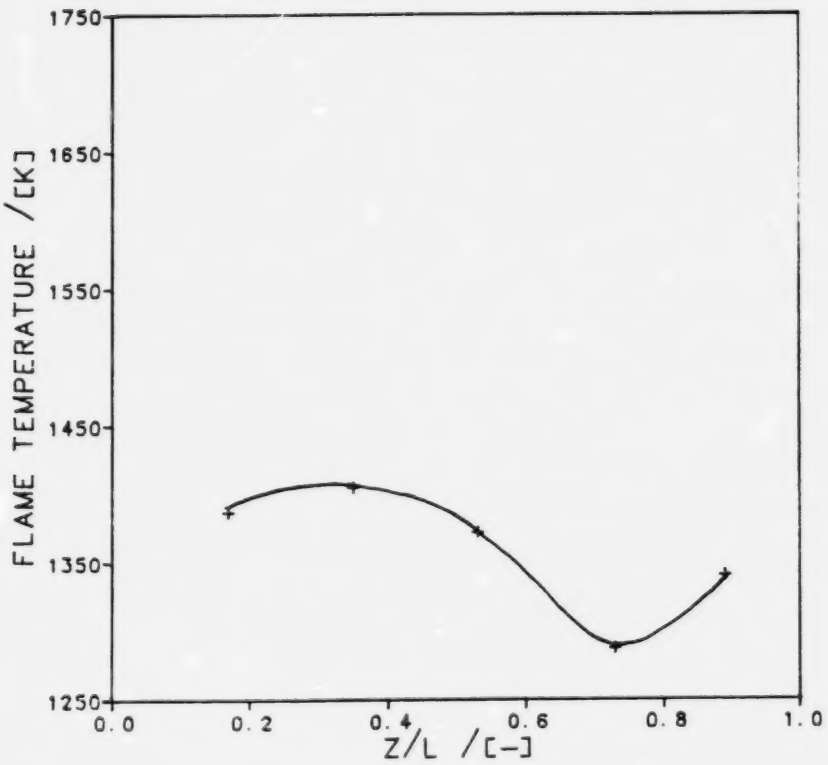
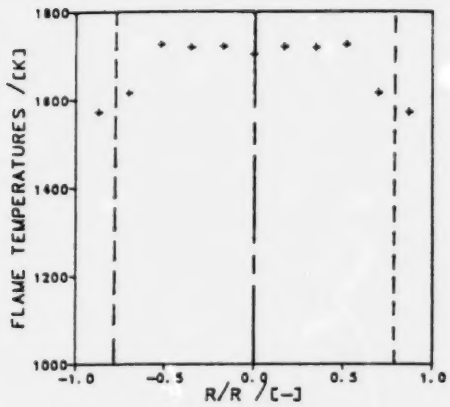
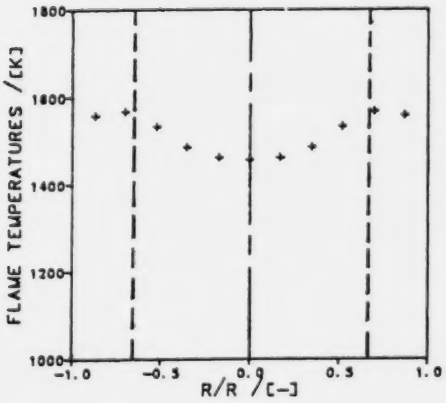


Fig. 4.10: Axial Temperature Profile for Test 5

Test 1



Z/L = 0.17
– – FLOW BOUNDARY



Z/L = 0.36
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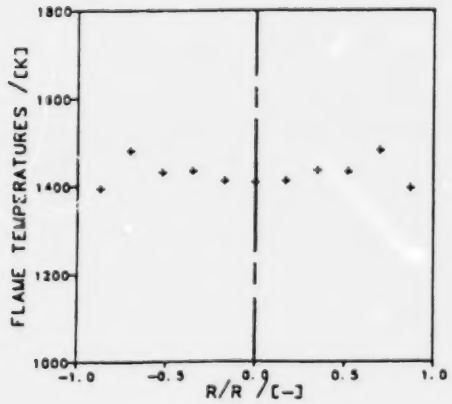
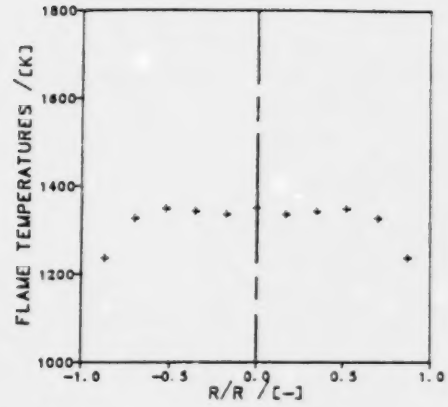


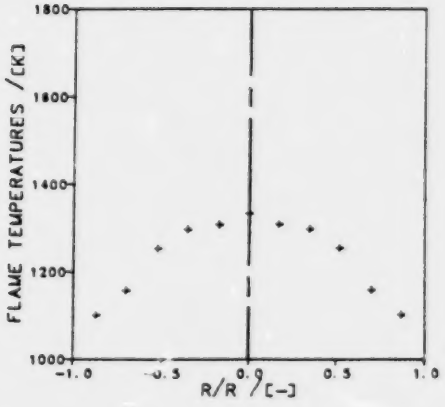
Z/L = 0.56

Fig. 4.11: Radial temperature profiles for Test 1

Test 1



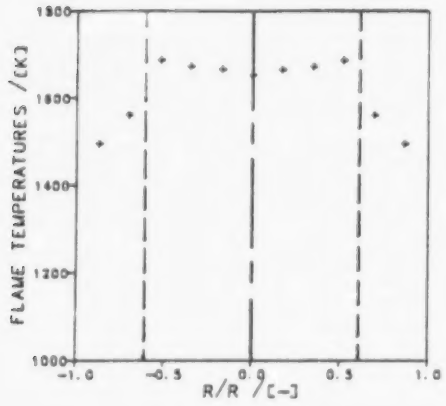
Z/L = 0.74



Z/L = 0.90

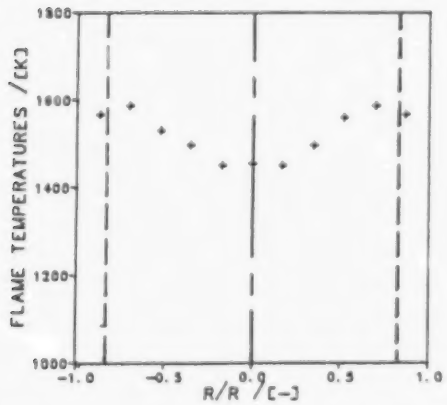
Fig. 4.11a: Radial temperature profiles for Test 1

Test 2



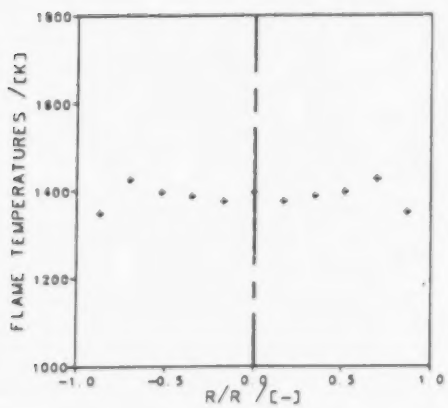
Z/L = 0.17

– – FLOW BOUNDARY



Z/L = 0.36

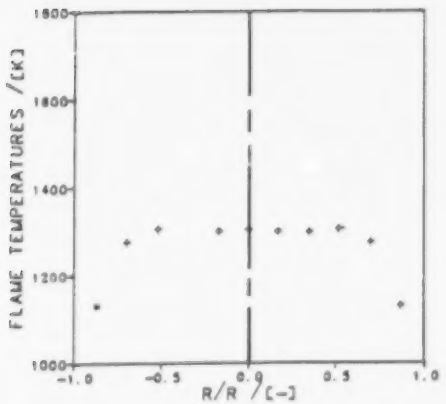
– – FLOW BOUNDARY



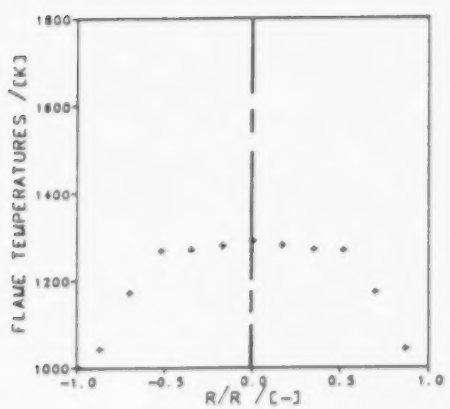
Z/L = 0.56

Fig. 4.12: Radial temperature profiles for Test 2

Test 2



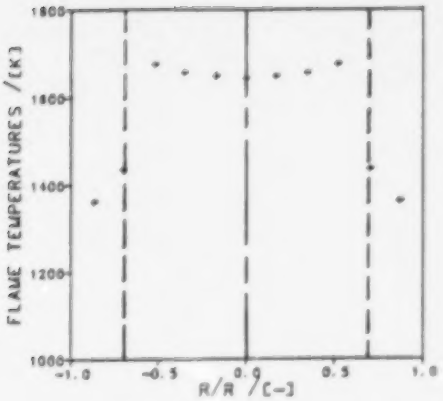
Z/L = 0.74



Z/L = 0.90

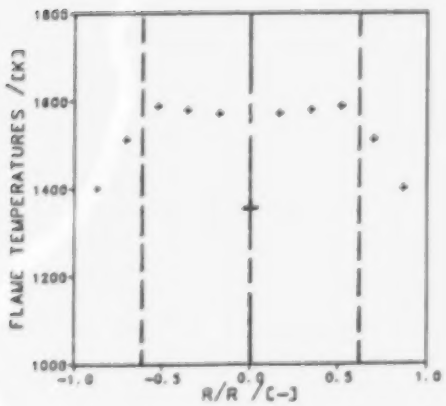
Fig. 4.12a: Radial temperature profiles for Test 2

Test 3



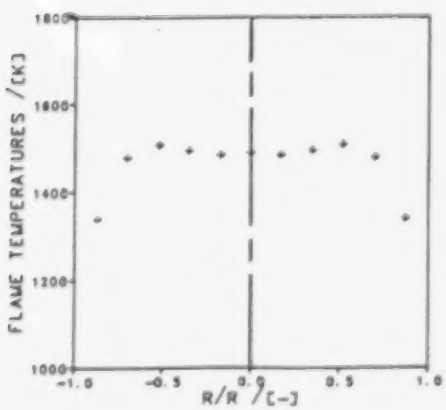
Z/L = 0.17

– – FLOW BOUNDARY



Z/L = 0.35

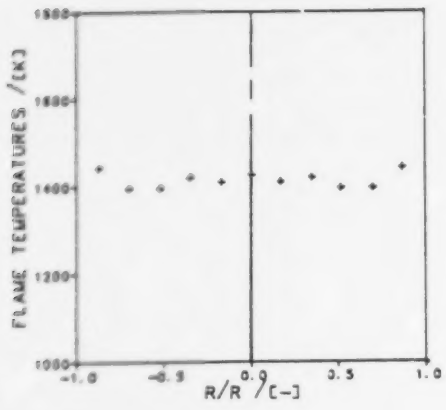
– – FLOW BOUNDARY



Z/L = 0.53

Fig. 4.13: Radial temperature profiles for Test 3

Test 3



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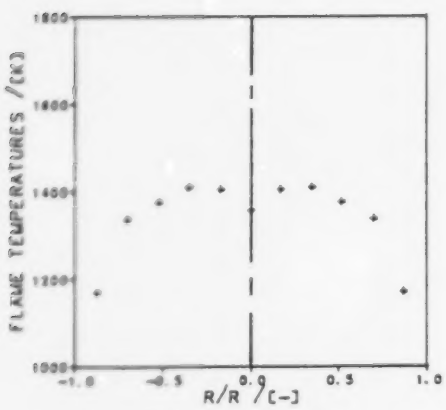
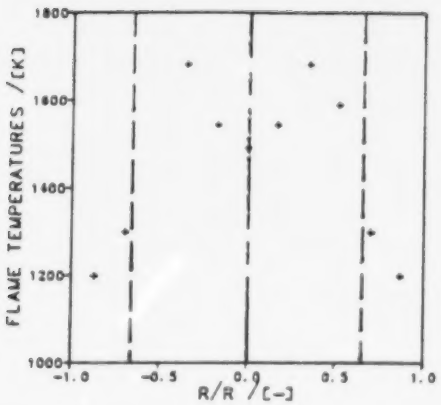


Z/L = 0.89

Fig. 4.13a: Radial temperature profiles for Test 3

Test 4



Z/L = 0.17

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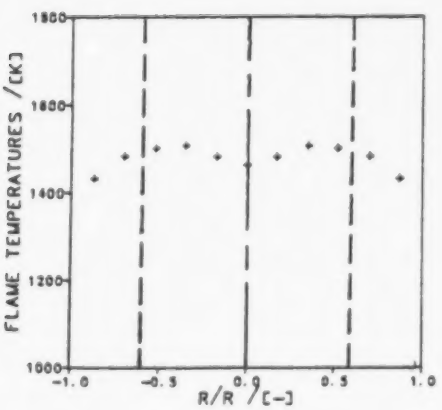

Z/L = 0.35

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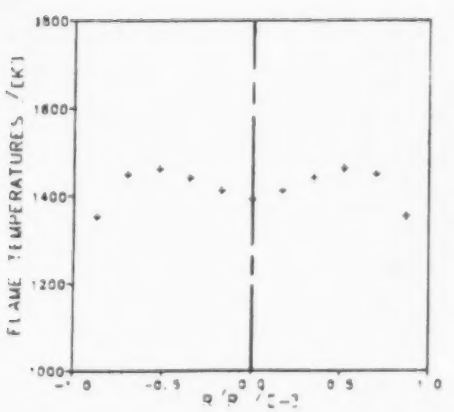
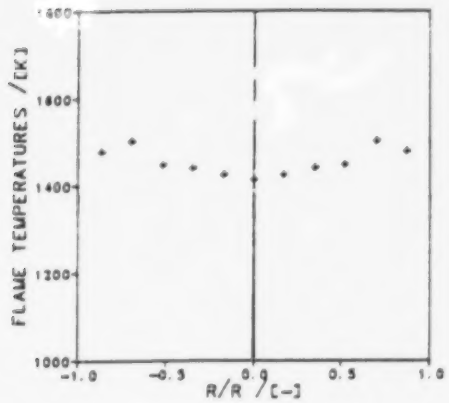


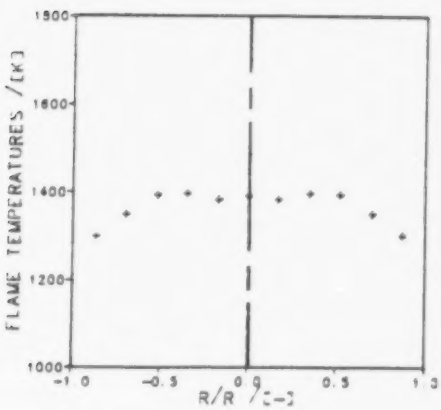
Z/L = 0.53

Fig. 4.14: Radial temperature profiles for Test 4

Test 4



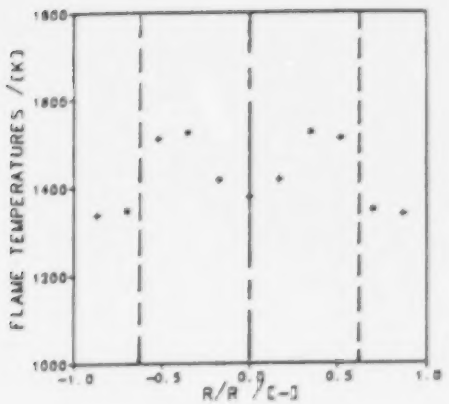
Z/L = 0.73



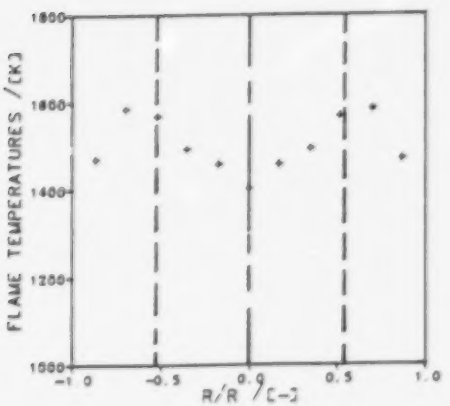
Z/L = 0.89

Fig. 4.14a: Radial temperature profiles for Test 4

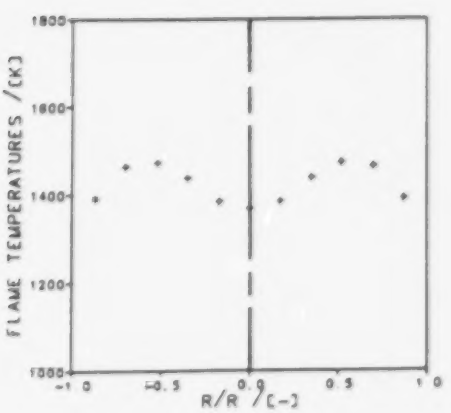
Test 5



Z/L = 0.17
– – FLOW BOUNDARY



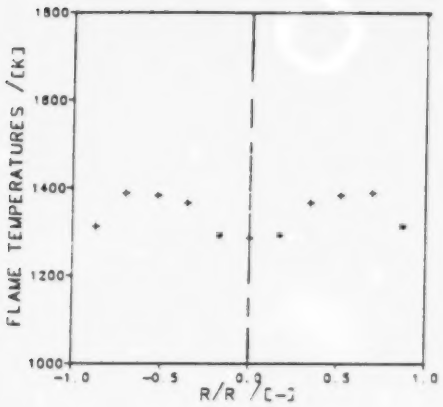
Z/L = 0.35
– – FLOW BOUNDARY



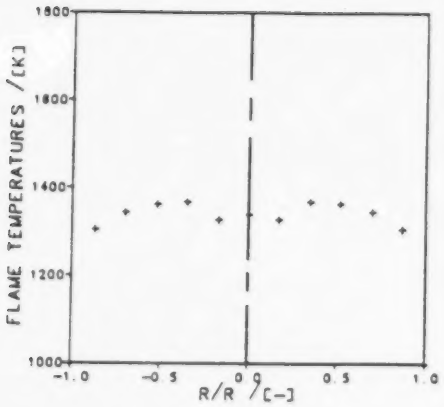
Z/L = 0.53

Fig. 4.15: Radial temperature profiles for Test 5

Test 5



Z/L = 0.73



Z/L = 0.89

Fig. 4.15a: Radial temperature profiles for Test 5

4.3 Gas composition profiles

The gas composition profiles for each test are summarised in Tables 4.6 to 4.23. This data is also plotted in graphical form (Figs 4.16 to 4.49) to show both the radial and axial variation of gas composition. Figures 4.26 to 4.37 have lines superimposed on them indicating the radial location of flow boundaries and peak flame temperatures. The raw gas data is reported in Appendix VII.

Table 4.6: Gas Composition, Test No. 1, Port 1b, Z/L = 0.17

r/R [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0	12.79 ±0.05	3.74 ±0.00	0.178 ±0.003	0.032 ±0.001	0.35 ±0.06
0.17	12.91 ±0.05	3.74 ±0.00	0.184 ±0.003	0.036 ±0.001	0.26 ±0.07
0.35	12.72 ±0.05	3.74 ±0.00	0.181 ±0.002	0.034 ±0.001	0.56 ±0.08
0.52	13.05 ±0.16	3.60 ±0.10	0.182 ±0.002	0.038 ±0.001	0.61 ±0.05
0.78	11.86 ±0.09	0.14 ±0.02	0.139 ±0.002	0.035 ±0.000	5.04 ±0.10

Table 4.7: Gas Composition, Test No. 1, Port 2b, Z/L = 0.36

r/R [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0	12.64 ±0.08	0.051 ±0.012	0.102 ±0.011	0.029 ±0.001	4.45 ±0.26
0.17	12.93 ±0.05	0.139 ±0.023	0.136 ±0.003	0.032 ±0.000	3.88 ±0.11
0.35	13.61 ±0.08	0.394 ±0.063	0.146 ±0.002	0.034 ±0.000	2.75 ±0.25
0.52	14.20 ±0.12	0.589 ±0.100	0.155 ±0.003	0.037 ±0.001	1.71 ±0.24
0.70	14.40 ±0.08	0.389 ±0.049	0.157 ±0.001	0.039 ±0.001	1.50 ±0.17
0.87	12.27 ±0.24	0.050 ±0.008	0.132 ±0.005	0.032 ±0.001	4.69 ±0.77

Table 4.8: Gas Composition, Test No. 1, Ports 3b, 4b, 5b, breeching, r/R = 0

Z/L [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0.56 (Port 3b)	11.93 ±0.10	0.004 ±0.001	0.093 ±0.004	0.026 ±0.000	5.48 ±0.09
0.74 (Port 4b)	12.23 ±0.06	0.003 ±0.001	0.091 ±0.005	0.026 ±0.001	5.06 ±0.09
0.90 (Port 5b)	12.75 ±0.06	0.002 ±0.001	0.106 ±0.010	0.028 ±0.001	4.53 ±0.32
1.13 (Breeching)	12.25 ±0.03	0.003 ±0.001	0.130 ±0.007	0.032 ±0.001	5.02 ±0.00

Table 4.9: Gas Composition, Test No. 2, Port 1b, Z/L = 0.17

r/R [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0	13.50 ±0.06	2.68 ±0.23	0.140 ±0.002	0.026 ±0.001	1.24 ±0.11
0.17	13.21 ±0.07	2.77 ±0.40	0.139 ±0.002	0.026 ±0.001	1.60 ±0.10
0.35	13.15 ±0.14	3.05 ±0.52	0.143 ±0.003	0.026 ±0.001	1.40 ±0.20
0.52	13.22 ±0.08	3.19 ±0.26	0.145 ±0.022	0.027 ±0.001	1.18 ±0.12
0.70	12.98 ±0.40	0.75 ±0.87	0.124 ±0.014	0.032 ±0.001	3.27 ±1.34

Table 4.10: Gas Composition, Test No. 2, Port 2b, Z/L = 0.36

r/R [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0	12.21 ±0.17	0.004 ±0.002	0.114 ±0.005	0.029 ±0.001	4.92 ±0.21
0.17	11.93 ±0.12	0.008 ±0.005	0.087 ±0.008	0.028 ±0.000	5.27 ±0.15
0.35	12.43 ±0.28	0.033 ±0.013	0.059 ±0.005	0.029 ±0.000	4.59 ±0.30
0.52	13.59 ±0.18	0.155 ±0.028	0.083 ±0.006	0.030 ±0.000	3.00 ±0.30
0.70	13.46 ±0.14	0.166 ±0.249	0.091 ±0.001	0.030 ±0.000	3.20 ±0.25
0.87	12.43 ±0.27	0.045 ±0.018	0.079 ±0.003	0.030 ±0.011	4.94 ±0.35

Table 4.11: Gas Composition, Test No. 2, Ports 3b, 4b, 5b, breeching, r/R = 0

Z/L [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0.56 (Port 3b)	12.06 ±0.40	0.002 ±0.001	0.114 ±0.002	0.029 ±0.000	5.08 ±0.44
0.74 (Port 4b)	12.49 ±0.19	0.002 ±0.001	0.108 ±0.006	0.029 ±0.001	4.55 ±0.25
0.90 (Port 5b)	12.94 ±0.17	0.002 ±0.001	0.109 ±0.003	0.029 ±0.000	3.85 ±0.22
1.13 (Breeching)	11.65 ±0.10	0.002 ±0.001	0.119 ±0.024	0.028 ±0.000	5.51 ±0.15

Table 4.12: Gas Composition, Test No. 3, Port 1b, Z/L = 0.17

r/R [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0	14.24 ±0.10	0.017 ±0.001	0.044 ±0.003	0.071 ±0.001	4.05 ±0.23
0.17	14.49 ±0.10	0.027 ±0.002	0.050 ±0.001	0.075 ±0.001	3.51 ±0.12
0.35	14.85 ±0.23	0.092 ±0.022	0.048 ±0.005	0.081 ±0.001	3.04 ±0.30
0.52	14.57 ±0.16	0.125 ±0.032	0.037 ±0.003	0.080 ±0.001	3.04 ±0.46
0.70	11.08 ±0.10	0.078 ±0.005	0.018 ±0.000	0.060 ±0.001	7.56 ±0.15
0.87	10.67 ±0.23	0.079 ±0.007	0.012 ±0.001	0.052 ±0.001	8.03 ±0.17

Table 4.13: Gas Composition, Test No. 3, Port 2b, Z/L = 0.35

r/R [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0	14.28 ±0.11	0.012 ±0.001	0.072 ±0.003	0.072 ±0.001	3.77 ±0.10
0.17	14.61 ±0.21	0.014 ±0.001	0.068 ±0.006	0.077 ±0.001	3.22 ±0.29
0.35	14.63 ±0.15	0.016 ±0.001	0.066 ±0.002	0.081 ±0.001	3.15 ±0.21
0.70	14.25 ±0.06	0.023 ±0.001	0.058 ±0.003	0.082 ±0.001	3.67 ±0.07
0.87	11.70 ±0.58	0.025 ±0.002	0.038 ±0.001	0.062 ±0.002	7.27 ±0.30

Table 4.14: Gas Composition, Test No. 3, Port 3b, Z/L = 0.53

r/R [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0	14.16 ±0.21	0.007 ±0.000	0.055 ±0.006	0.068 ±0.001	4.12 ±0.04
0.17	14.68 ±0.14	0.010 ±0.001	0.059 ±0.002	0.075 ±0.001	3.39 ±0.17
0.35	14.94 ±0.06	0.010 ±0.000	0.059 ±0.001	0.080 ±0.001	3.02 ±0.08
0.52	15.21 ±0.15	0.013 ±0.001	0.056 ±0.001	0.080 ±0.001	2.70 ±0.12
0.70	15.52 ±0.14	0.013 ±0.001	0.089 ±0.003	0.080 ±0.001	2.26 ±0.19
0.87	14.74 ±0.15	0.010 ±0.001	0.085 ±0.001	0.072 ±0.001	3.22 ±0.10

Table 4.15: Gas Composition, Test No. 3, Ports 4b, 5b, breeching, r/R = 0

Z/L [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0.73 (Port 4b)	14.39 ±0.05	0.005 ±0.000	0.066 ±0.004	0.065 ±0.000	3.86 ±0.05
0.89 (Port 5b)	15.15 ±0.07	0.005 ±0.000	0.064 ±0.006	0.065 ±0.000	2.86 ±0.06
1.21 (Breeching)	14.93 ±0.04	0.004 ±0.000	0.066 ±0.001	0.063 ±0.001	3.10 ±0.03

Table 4.16: Gas Composition, Test No. 4, Port 1b, Z/L = 0.17

r/R [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0	11.65 ±0.07	0.014 ±0.003	0.041 ±0.005	0.060 ±0.001	7.08 ±0.04
0.17	11.59 ±0.03	0.013 ±0.001	0.043 ±0.003	0.061 ±0.001	7.14 ±0.02
0.35	11.75 ±0.05	0.024 ±0.001	0.041 ±0.001	0.063 ±0.001	6.74 ±0.07
0.52	13.06 ±0.11	0.134 ±0.024	0.027 ±0.001	0.079 ±0.001	4.87 ±0.18
0.70	9.64 ±0.23	0.267 ±0.013	0.029 ±0.001	0.062 ±0.001	8.76 ±0.21
0.87	6.97 ±0.75	0.426 ±0.006	0.027 ±0.004	0.045 ±0.005	12.14 ±0.61

Table 4.17: Gas Composition, Test No. 4, Port 2b, Z/L = 0.35

r/R [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0	11.07 ±0.20	0.014 ±0.000	0.063 ±0.002	0.043 ±0.002	7.84 ±0.13
0.17	10.96 ±0.38	0.014 ±0.003	0.064 ±0.001	0.043 ±0.004	7.77 ±0.18
0.35	11.96 ±0.07	0.015 ±0.000	0.032 ±0.001	0.063 ±0.002	6.68 ±0.09
0.52	11.98 ±0.06	0.017 ±0.001	0.033 ±0.001	0.069 ±0.000	6.58 ±0.04
0.70	12.27 ±0.03	0.021 ±0.000	0.034 ±0.001	0.077 ±0.001	6.27 ±0.07
0.87	10.56 ±0.08	0.037 ±0.002	0.031 ±0.002	0.057 ±0.001	8.23 ±0.02

Table 4.18: Gas Composition, Test No. 4, Port 3b, Z/L = 0.53

r/R [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0	12.16 ±0.07	0.011 ±0.001	0.034 ±0.002	0.048 ±0.001	6.68 ±0.06
0.17	11.80 ±0.06	0.013 ±0.001	0.041 ±0.002	0.043 ±0.001	7.23 ±0.03
0.35	13.06 ±0.18	0.011 ±0.001	0.034 ±0.005	0.056 ±0.002	5.70 ±0.21
0.52	12.46 ±0.05	0.013 ±0.000	0.063 ±0.002	0.055 ±0.001	6.37 ±0.02
0.70	13.33 ±0.07	0.014 ±0.001	0.070 ±0.001	0.062 ±0.001	5.39 ±0.10
0.87	10.56 ±0.71	0.016 ±0.001	0.060 ±0.023	0.051 ±0.006	8.50 ±0.21

Table 4.19: Gas Composition, Test No. 4, Ports 4b, 5b, breeching, r/R = 0

Z/L [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0.73 (Port 4b)	12.85 ±0.04	0.006 ±0.001	0.095 ±0.001	0.058 ±0.001	5.84 ±0.06
0.89 (Port 5b)	13.44 ±0.05	0.006 ±0.000	0.094 ±0.019	0.060 ±0.001	5.25 ±0.05
1.21 (Breeching)	13.60 ±0.04	0.005 ±0.001	0.063 ±0.016	0.061 ±0.000	4.93 ±0.07

Table 4.20: Gas Composition, Test No. 5, Port 1b, Z/L = 0.17

r/R [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0	10.18 ±0.13	0.018 ±0.002	0.051 ±0.001	0.042 ±0.001	8.72 ±0.03
0.35	12.03 ±0.27	0.025 ±0.001	0.045 ±0.002	0.069 ±0.002	6.66 ±0.23

Table 4.21: Gas Composition, Test No. 5, Port 2b, Z/L = 0.35

r/R [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0	10.27 ±0.43	0.010 ±0.002	0.031 ±0.004	0.043 ±0.002	8.66 ±0.40
0.35	11.05 ±0.09	0.018 ±0.002	0.032 ±0.001	0.056 ±0.001	7.82 ±0.11
0.70	12.81 ±0.19	0.093 ±0.024	0.035 ±0.001	0.065 ±0.000	5.56 ±0.24

Table 4.22: Gas Composition, Test No. 5, Port 3b, Z/L = 0.53

r/R [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0	12.24 ±0.14	0.008 ±0.000	0.107 ±0.021	0.049 ±0.001	6.75 ±0.19
0.35	11.24 ±0.07	0.010 ±0.001	0.058 ±0.005	0.046 ±0.001	7.86 ±0.08
0.52	13.58 ±0.24	0.013 ±0.001	0.064 ±0.001	0.061 ±0.002	4.94 ±0.24
0.70	13.64 ±0.20	0.013 ±0.001	0.065 ±0.001	0.062 ±0.002	4.90 ±0.19

Table 4.23 Gas Composition, Test No. 5, Ports 4b, 5b, breeching, r/R = 0

Z/L [-]	CO_2	CO	SO_2 /[%]	NO_x	O_2
0.73 (Port 4b)	12.44 ±0.12	0.007 ±0.001	0.046 ±0.004	0.043 ±0.001	6.52 ±0.10
0.89 (Port 5b)	13.74 ±0.06	0.005 ±0.001	0.082 ±0.006	0.050 ±0.001	5.03 ±0.08
1.21 (breeching)	13.80 ±0.11	0.004 ±0.001	0.089 ±0.006	0.049 ±0.001	4.86 ±0.22

AXIAL VARIATION OF O_2 AND CO_2

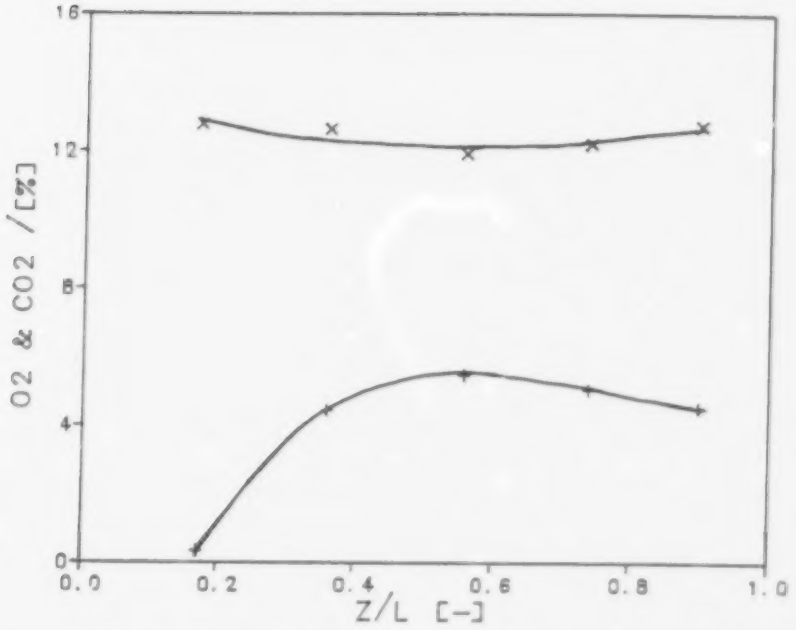


Fig. 4.16: Axial variation of O_2 and CO_2 for Test 1

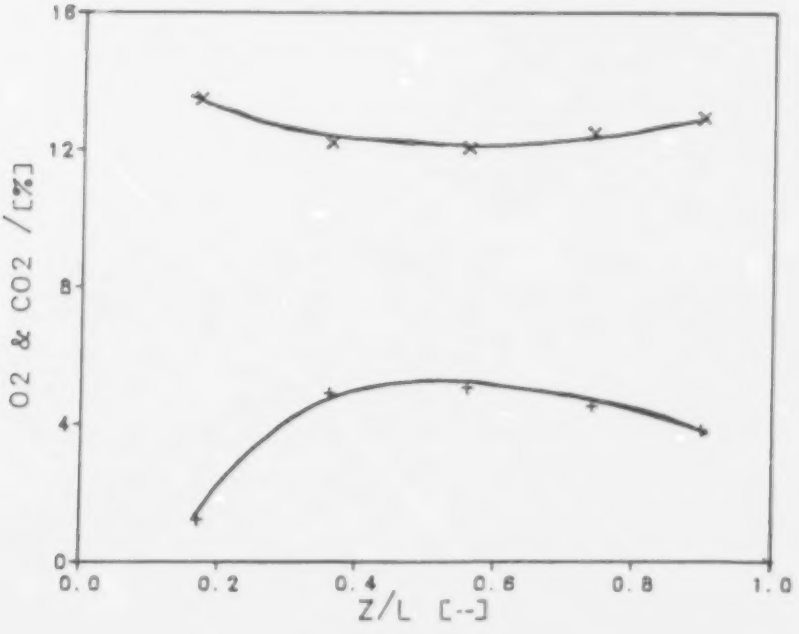


Fig. 4.17: Axial variation of O_2 and CO_2 for Test 2

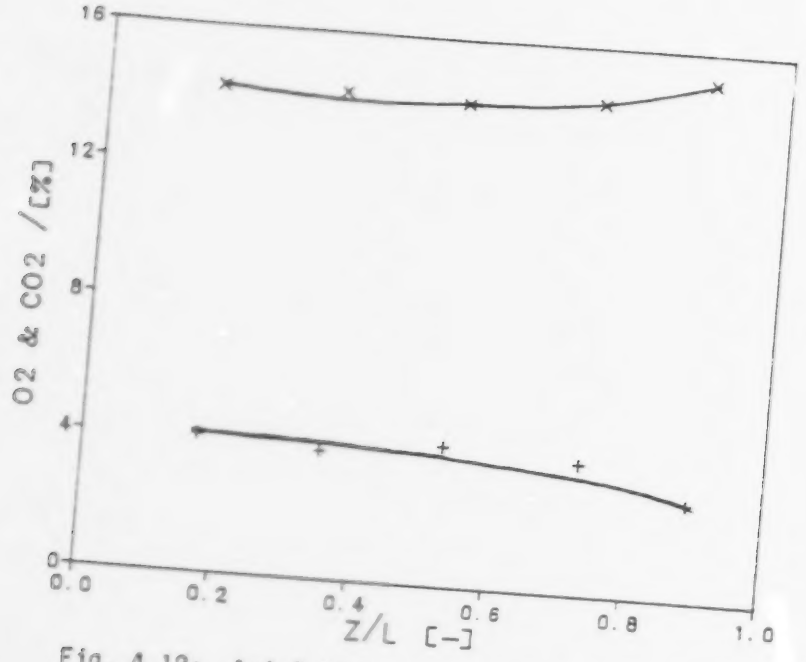


Fig. 4.18: Axial Variation of O_2 and CO_2 for Test 3

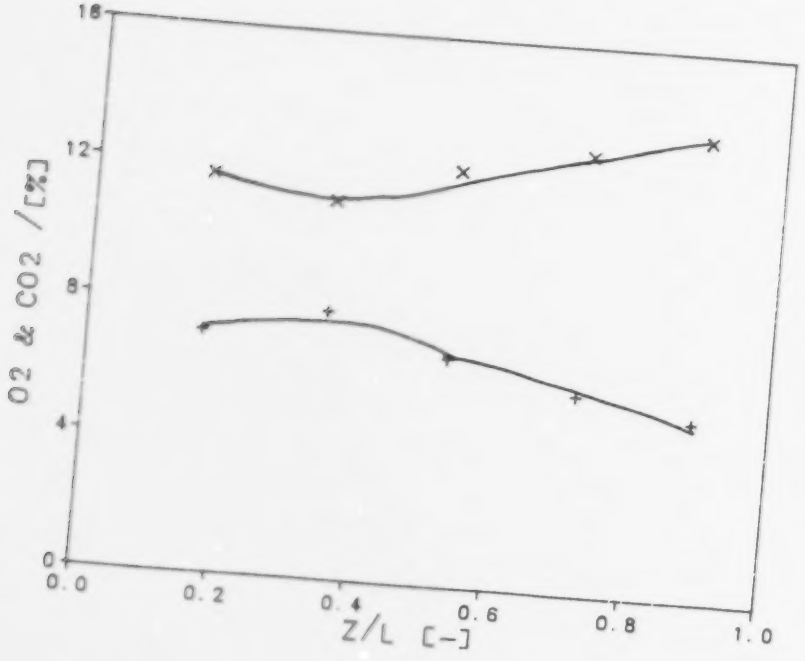


Fig. 4.19: Axial Variation of O_2 and CO_2 for Test 4

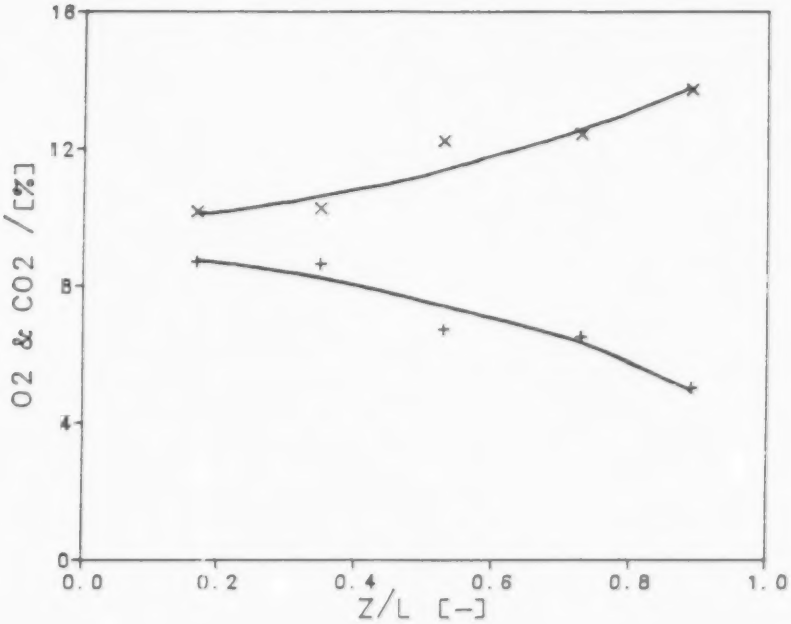


Fig. 4.20: Axial Variation of O_2 and CO_2 for Test 5

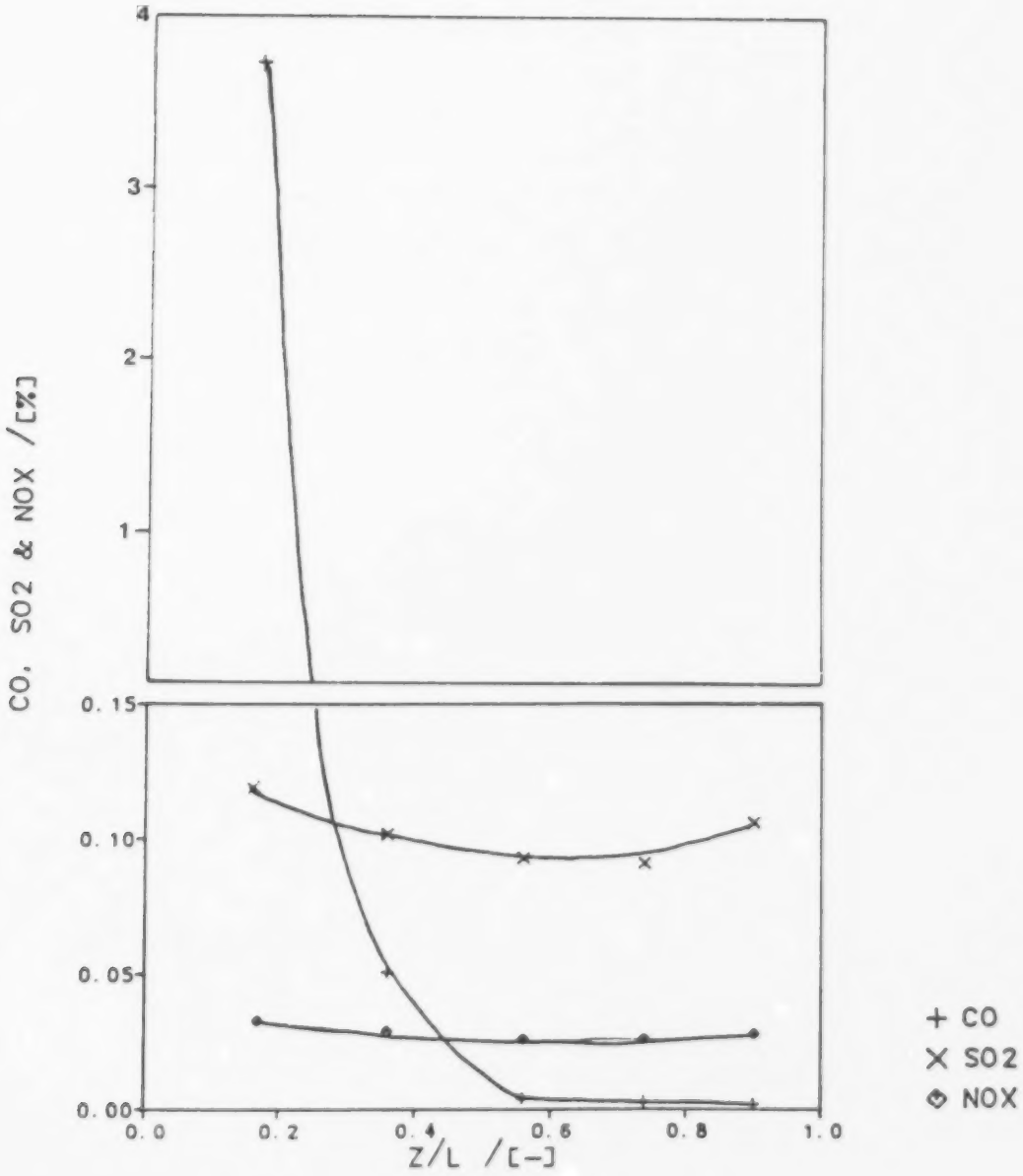


Fig. 4.21: Axial Variation of CO, SO_2 and NO_x for Test 1

AXIAL VARIATION OF CO, SO_2 AND NO_x

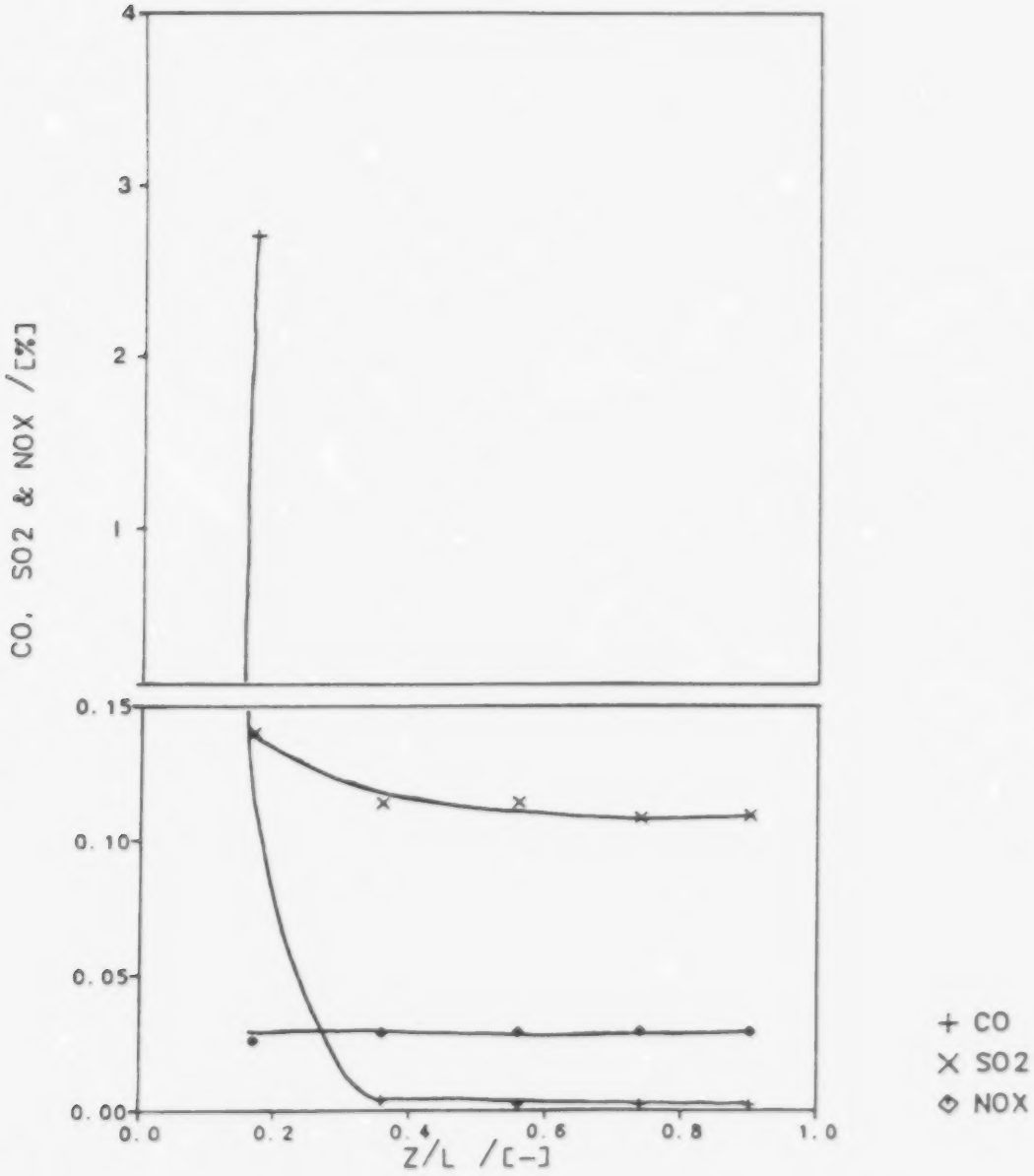


Fig. 4.22: Axial Variation of CO, SO_2 and NO_x for Test 2

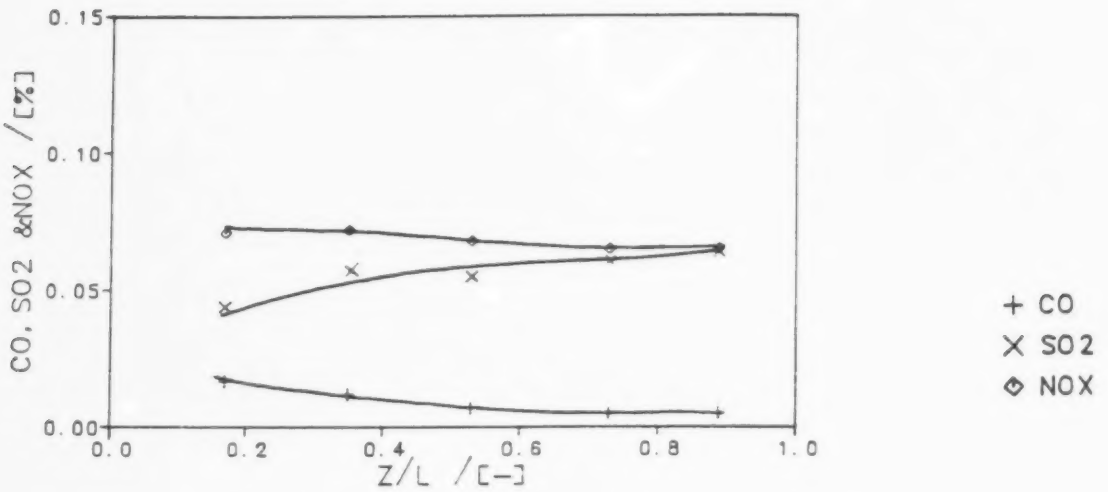


Fig. 4.23: Axial Variation of CO, SO_2 and NO_x for Test 3

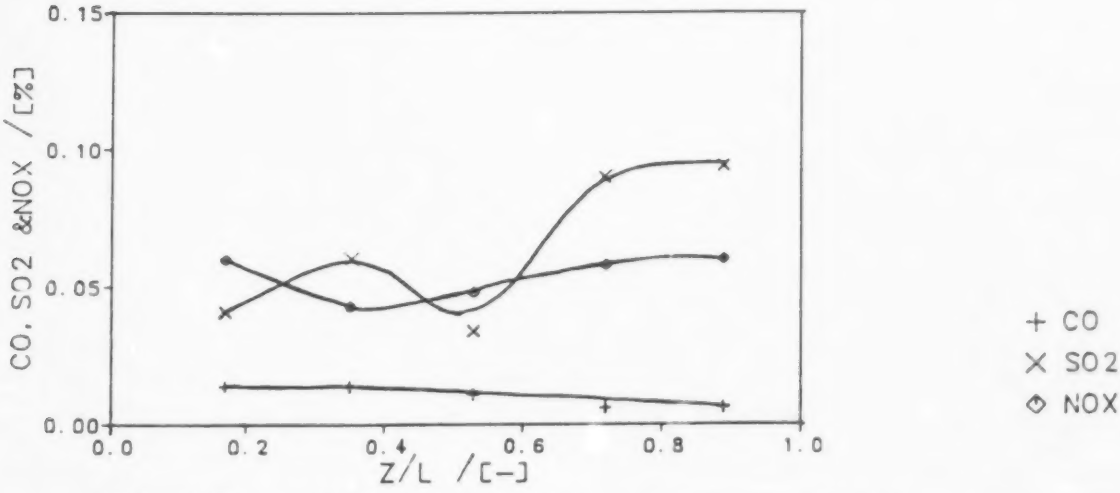


Fig. 4.24: Axial Variation of CO, SO_2 and NO_x for Test 4

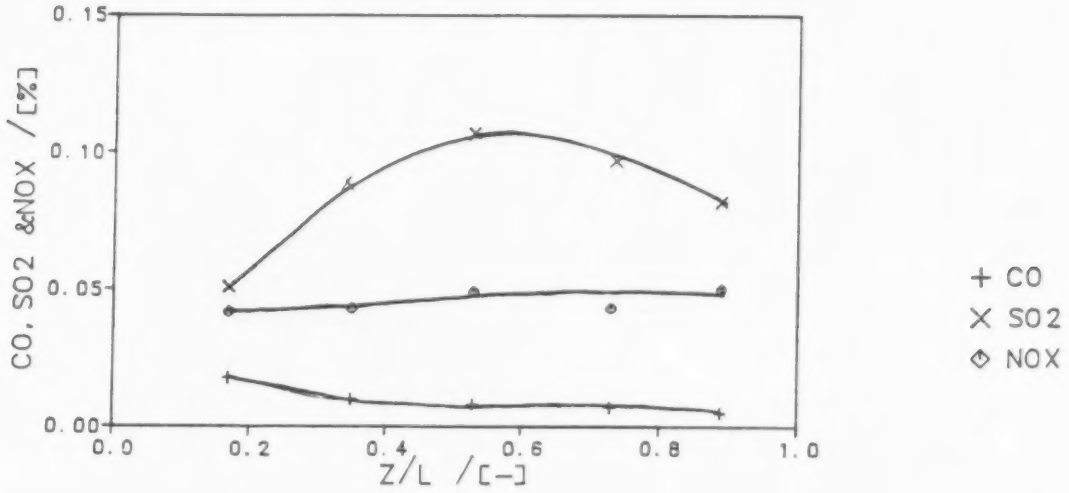


Fig. 4.25: Axial Variation of CO, SO_2 and NO_x for Test 5

RADIAL VARIATION OF O_2 AND CO_2

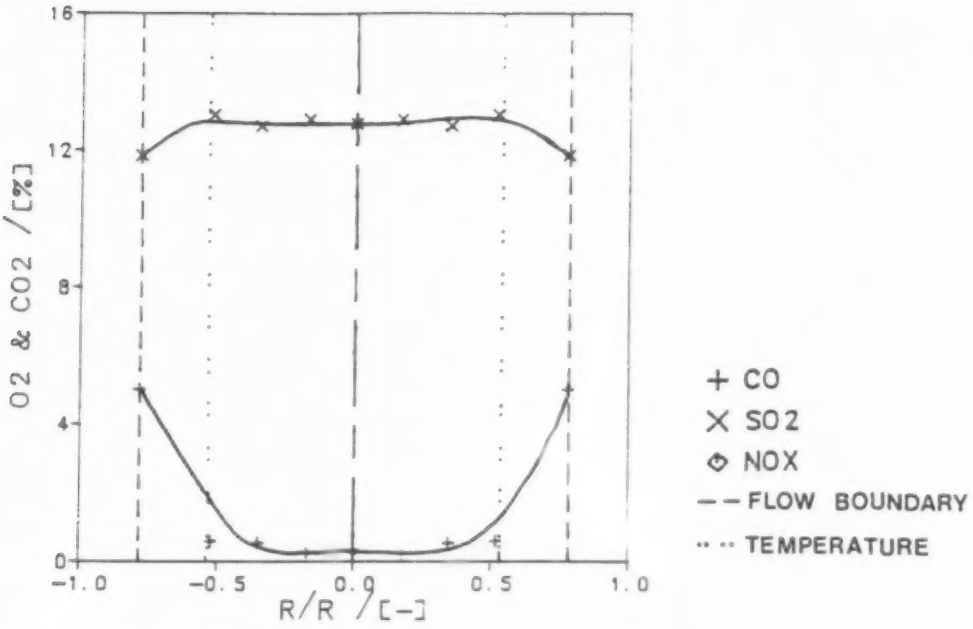


Fig. 4.26: Radial Variation of O_2 and CO_2 for Test 1; Z/L = 0.17

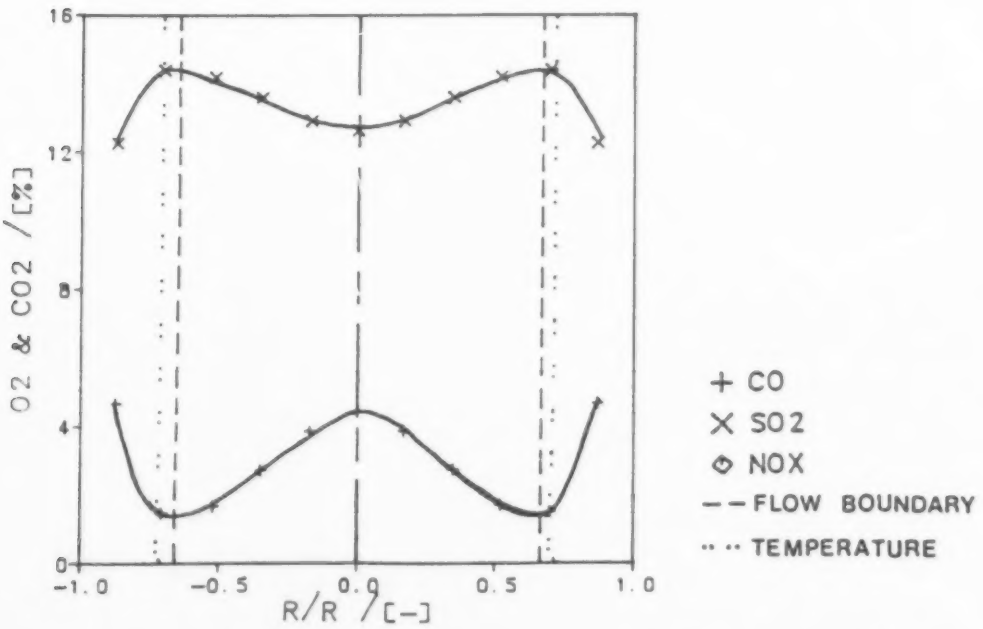


Fig. 4.27: Radial Variation of O_2 and CO_2 for Test 1; Z/L = 0.36

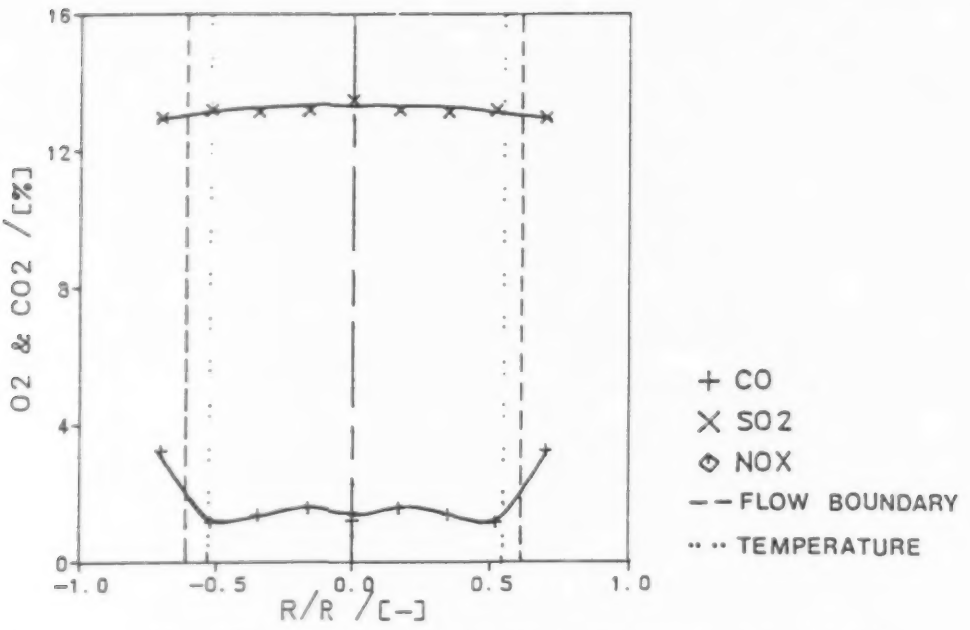


Fig. 4.28: Radial Variation of O_2 and CO_2 for Test 2; Z/L = 0.17

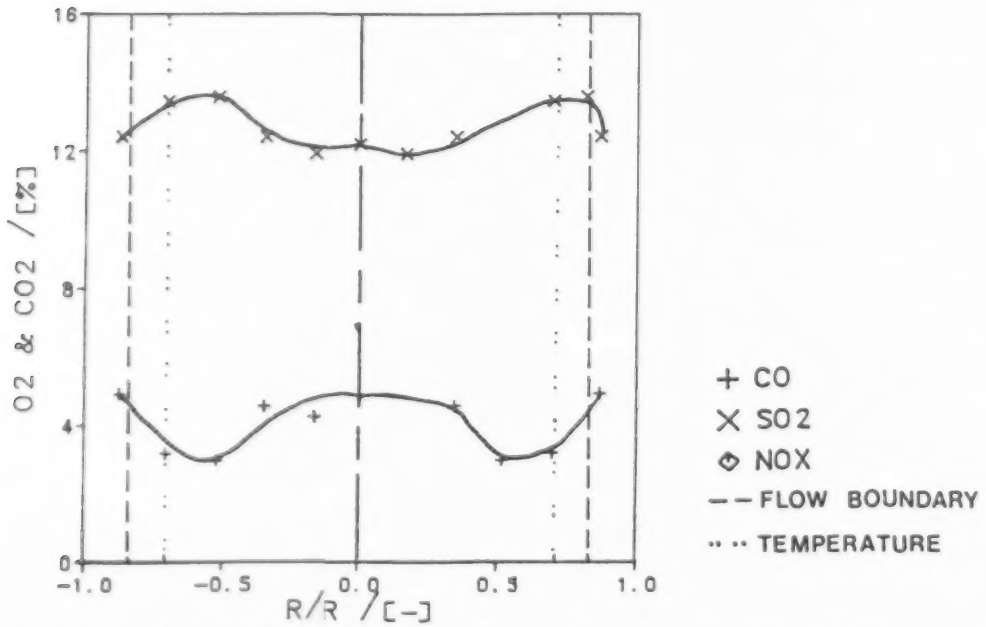


Fig. 4.29: Radial Variation of O_2 and CO_2 for Test 2; Z/L = 0.36

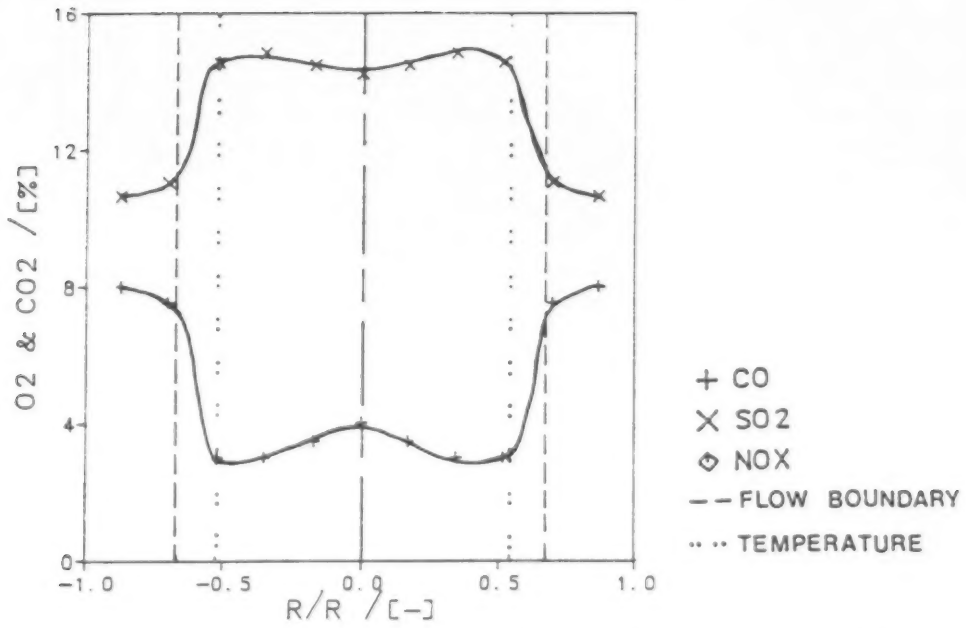


Fig. 4.30: Radial Variation of O_2 and CO_2 for Test 3; Z/L = 0.17

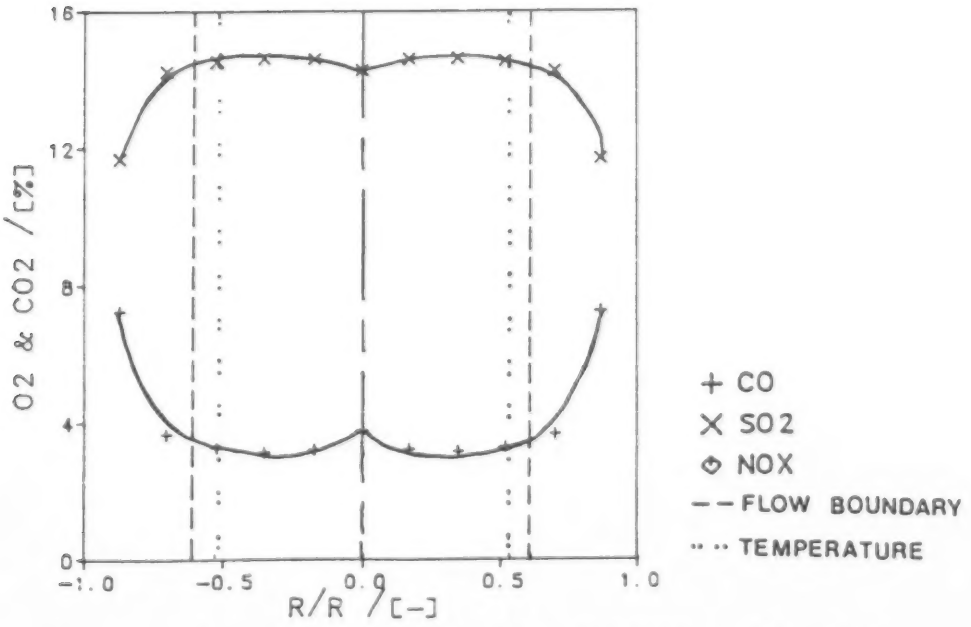


Fig. 4.31: Radial Variation of O_2 and CO_2 for Test 3; Z/L = 0.35

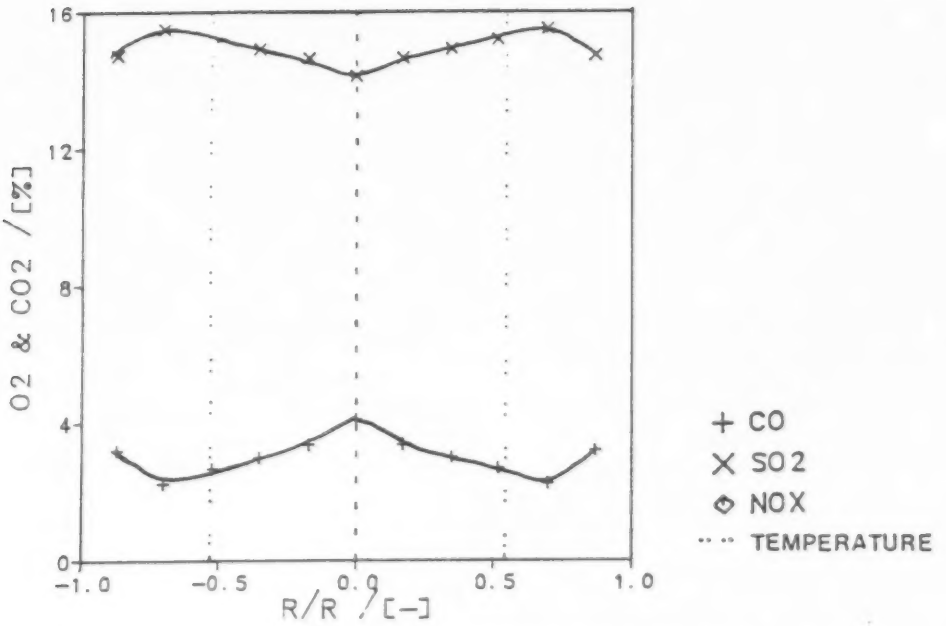


Fig. 4.32: Radial Variation of O_2 and CO_2 for Test 3; Z/L = 0.53

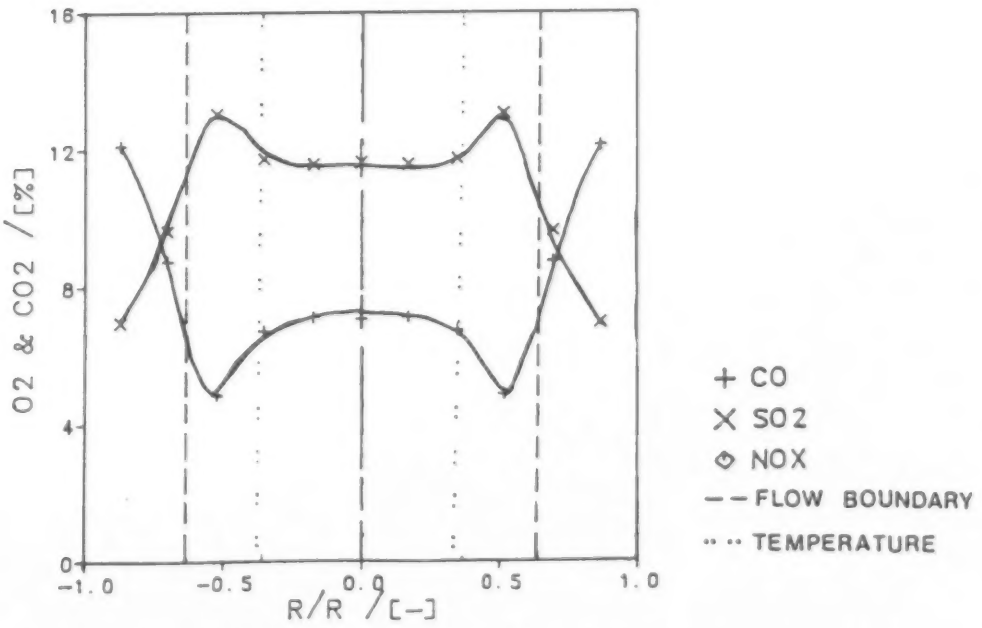


Fig. 4.33: Radial Variation of O_2 and CO_2 for Test 4; Z/L = 0.17

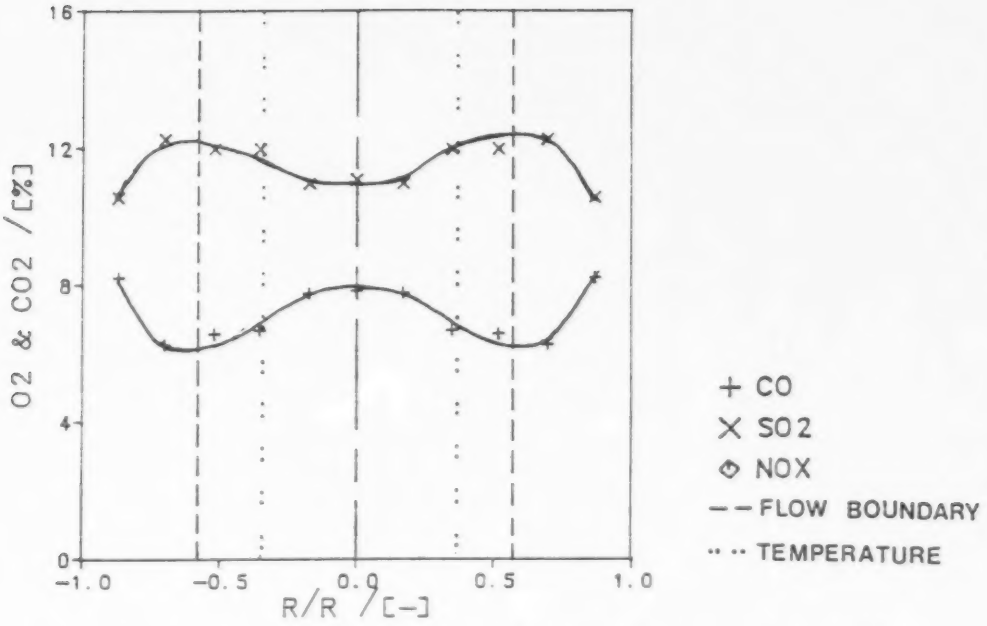


Fig. 4.34: Radial Variation of O_2 and CO_2 for Test 4; Z/L = 0.35

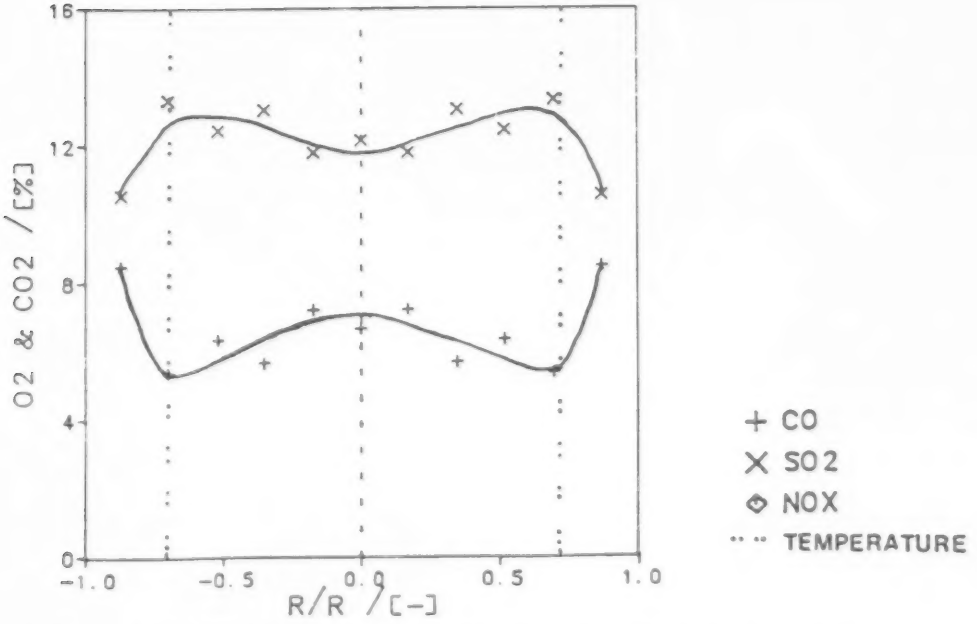


Fig. 4.35: Radial Variation of O_2 and CO_2 for Test 4; Z/L = 0.53

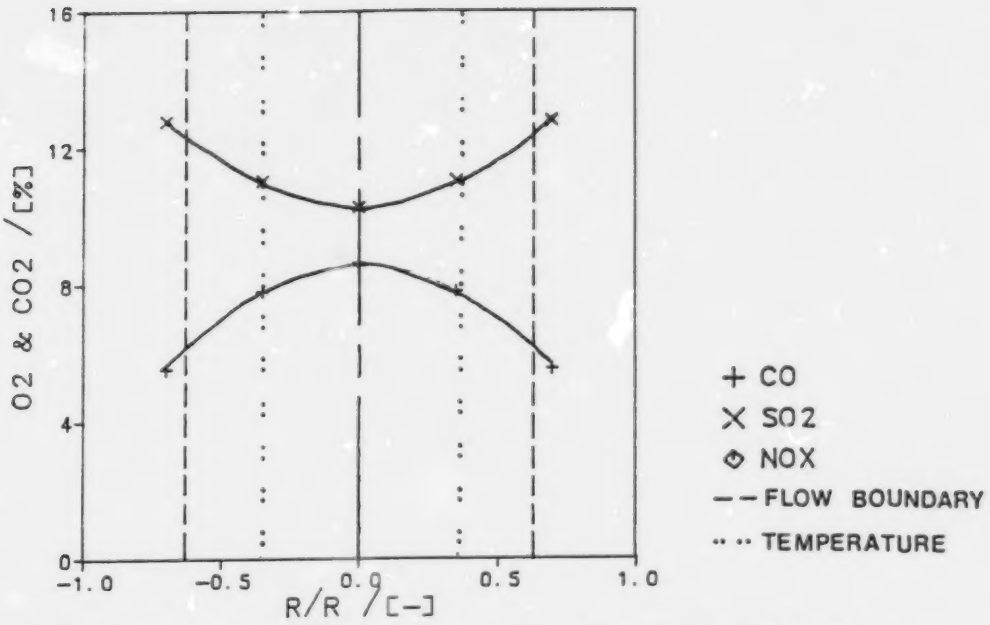


Fig. 4.36: Radial Variation of O_2 and CO_2 for Test 5; Z/L = 0.17

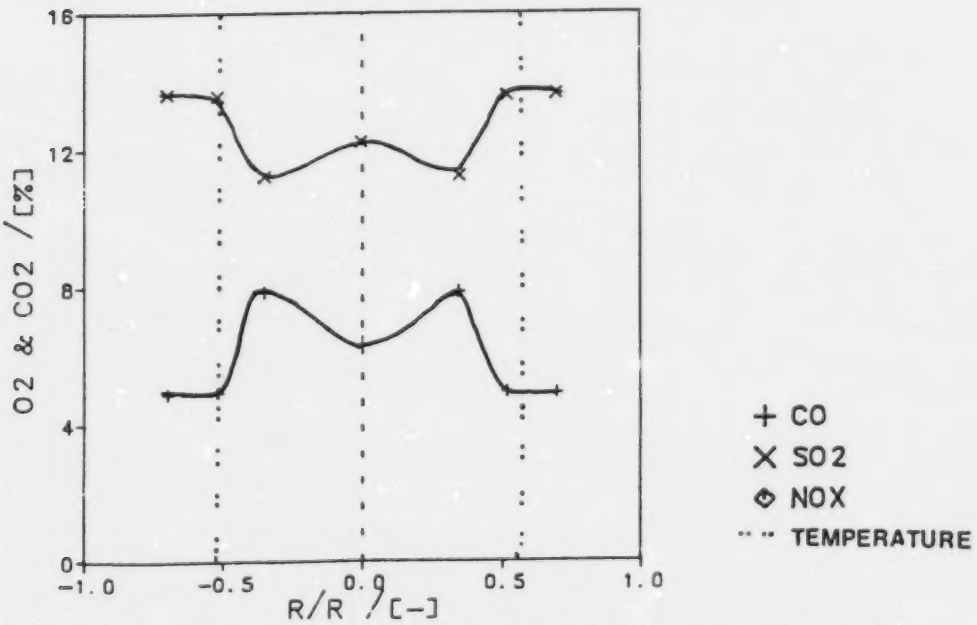


Fig. 4.37: Radial Variation of O_2 and CO_2 for Test 5; Z/L = 0.53

RADIAL VARIATION OF CO, SO_2 AND NO_x

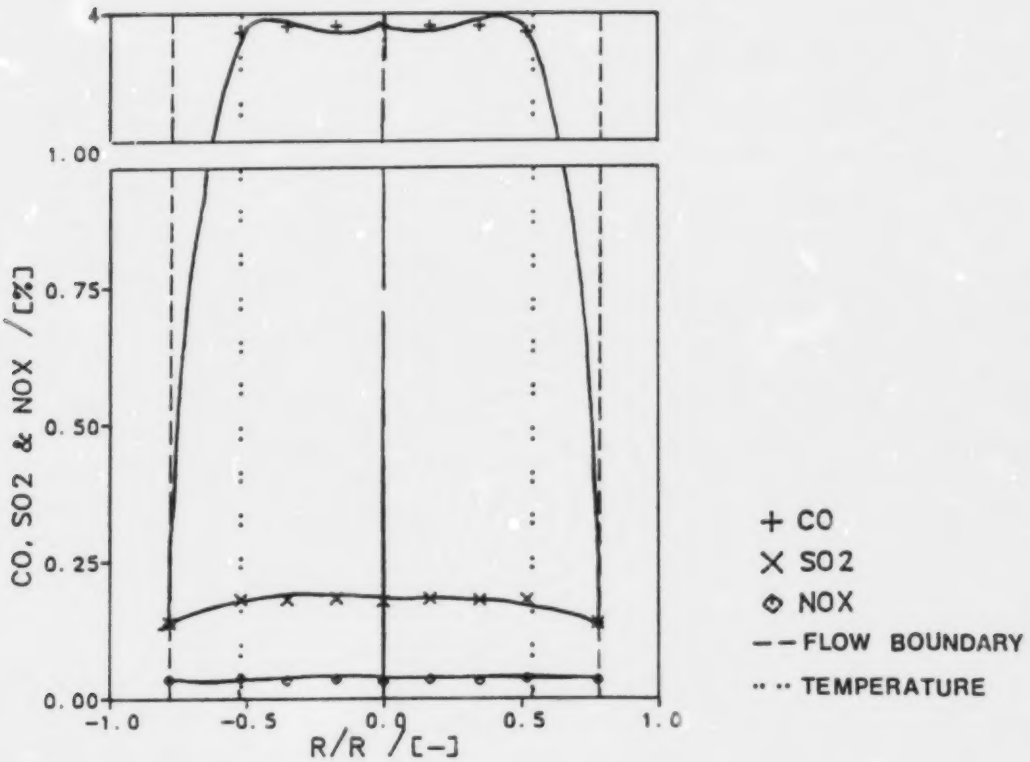


Fig. 4.38: Radial Variation of CO, SO_2 and NO_x for Test 1; Z/L = 0.17

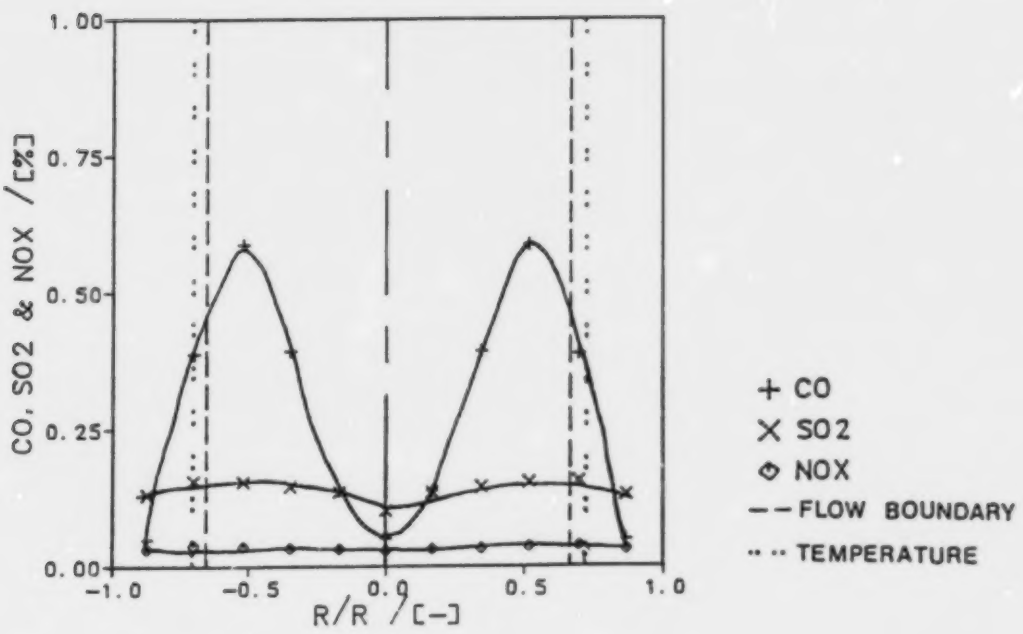


Fig. 4.39: Radial Variation of CO, SO_2 and NO_x for Test 1; Z/L = 0.36

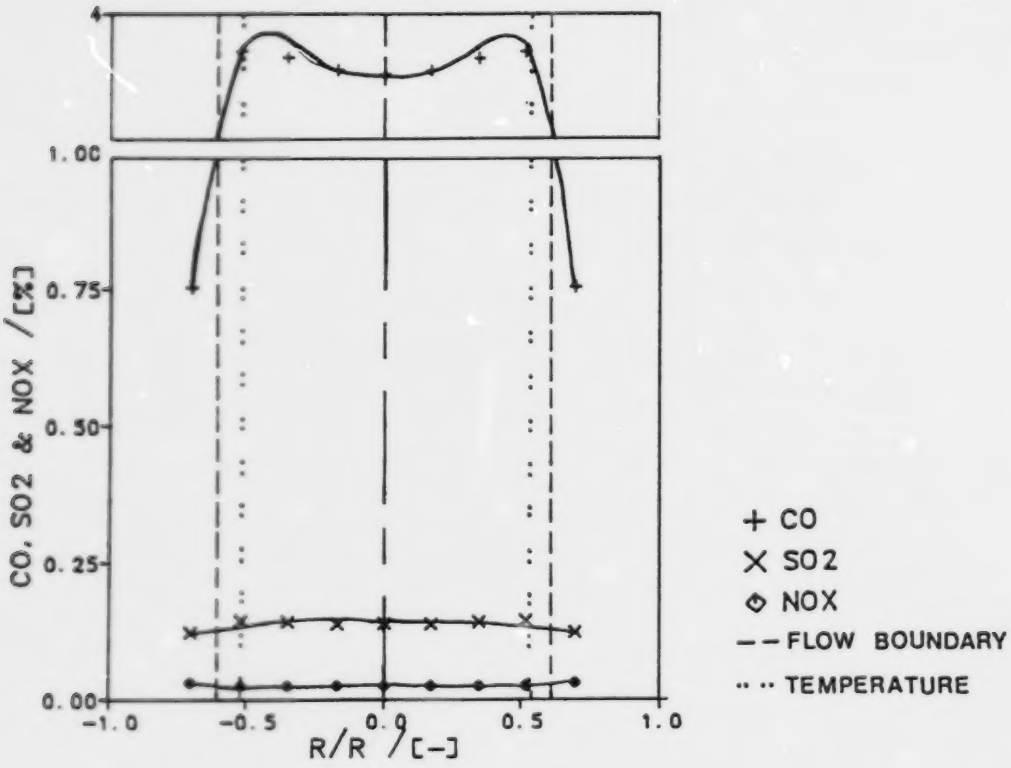


Fig. 4.40: Radial Variation of CO, SO_2 and NO_x for Test 2; Z/L = 0.17

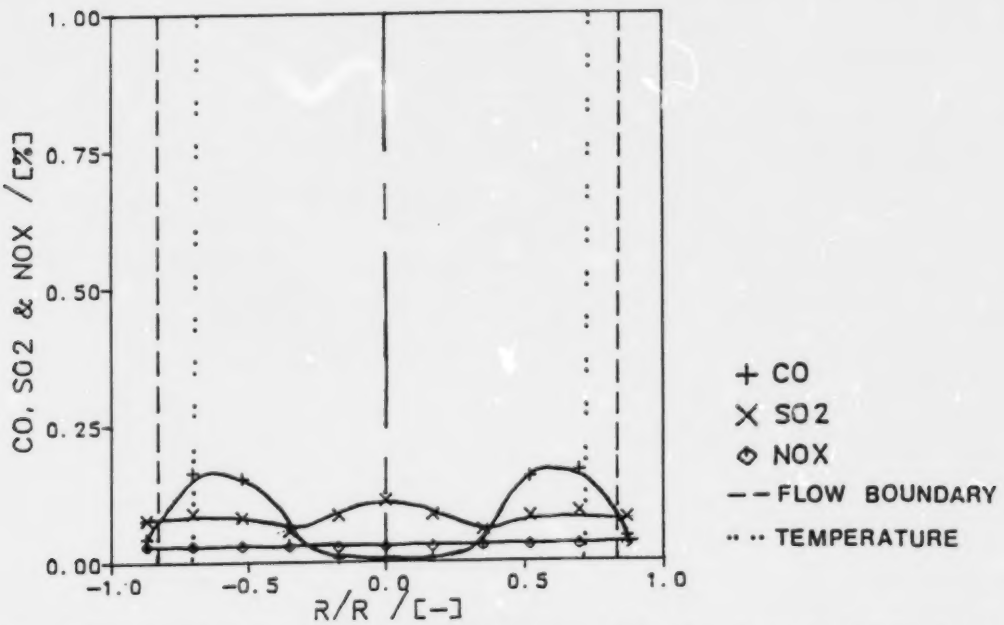


Fig. 4.41: Radial Variation of CO, SO_2 and NO_x for Test 2; Z/L = 0.36

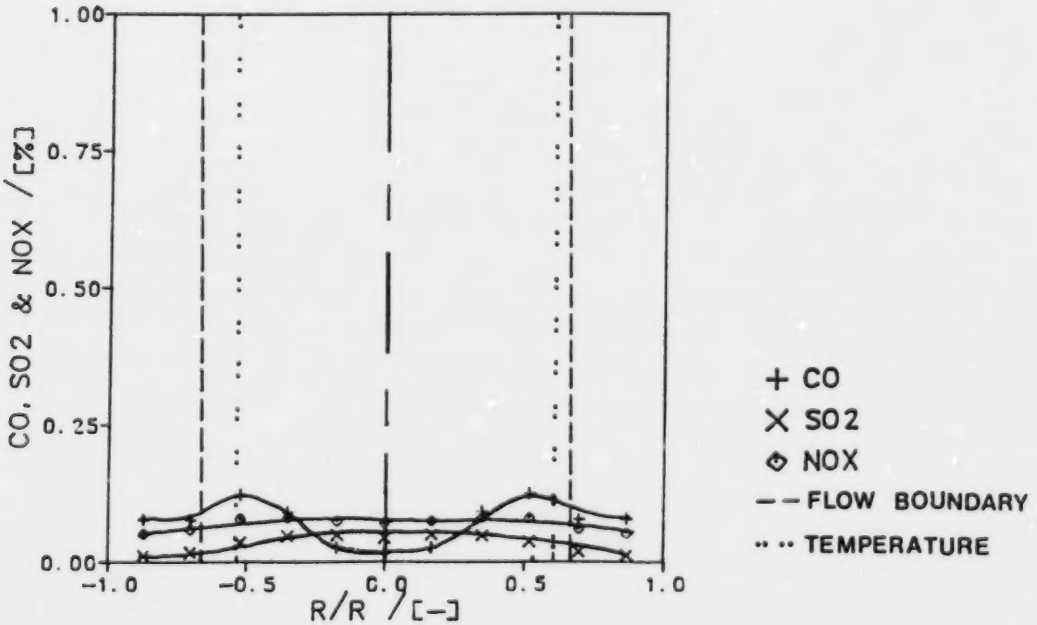


Fig. 4.42: Radial Variation of CO, SO_2 and NO_x for Test 3; Z/L = 0.17

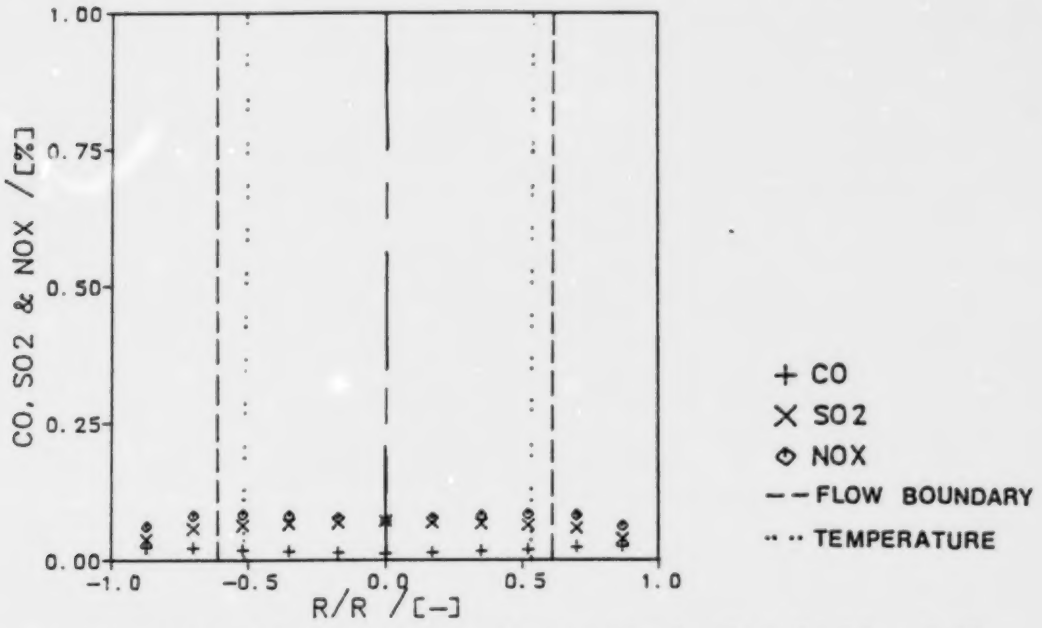


Fig. 4.43: Radial Variation of CO, SO_2 and NO_x for Test 3; Z/L = 0.35

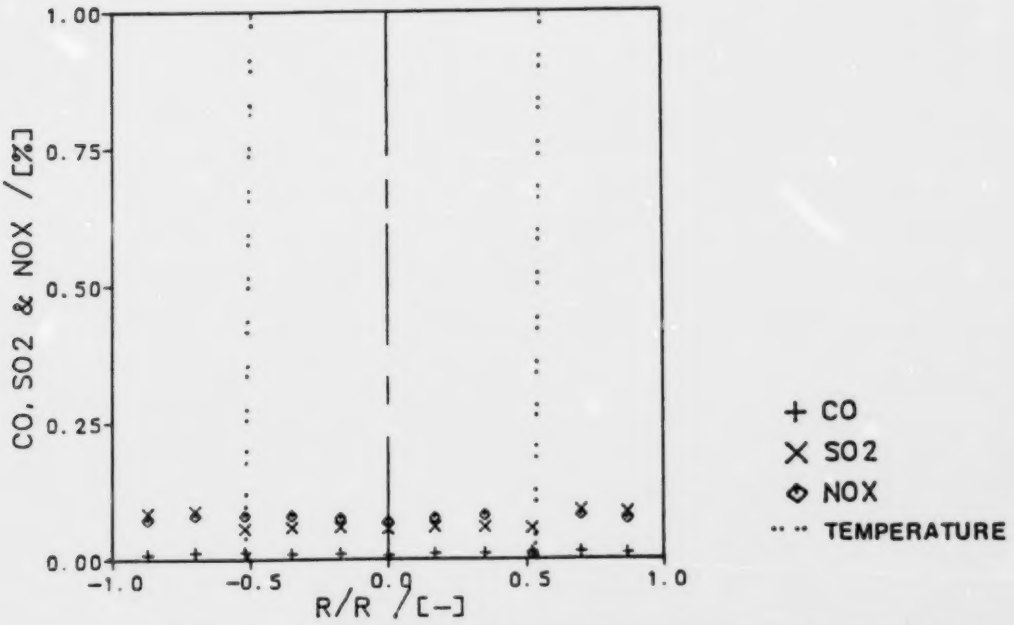


Fig. 4.44: Radial Variation of CO, SO_2 and NO_x for Test 3; Z/L = 0.53

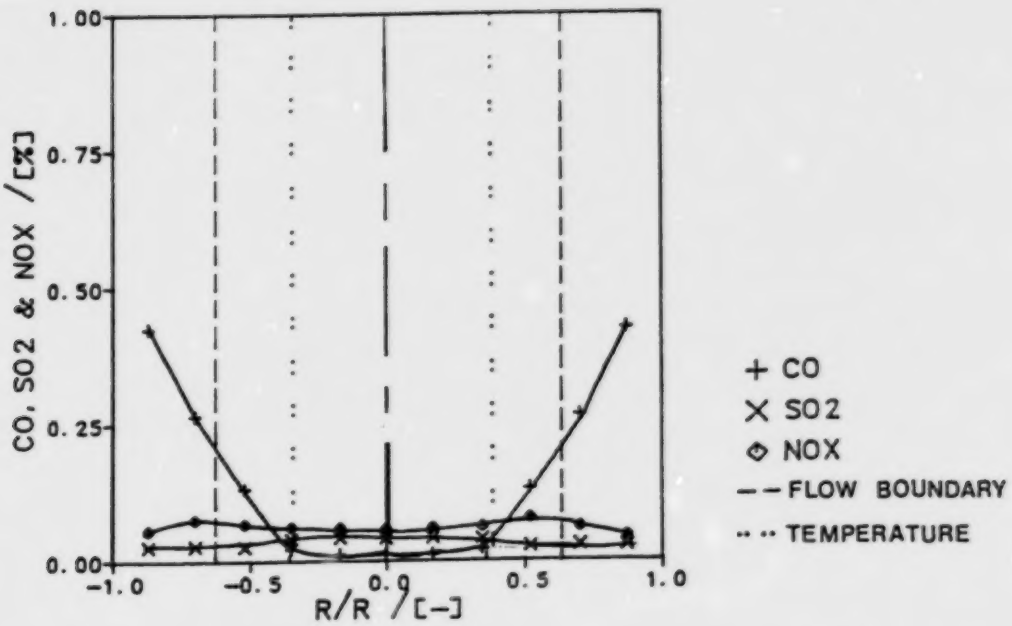


Fig. 4.45: Radial Variation of CO, SO_2 and NO_x for Test 4; Z/L = 0.17

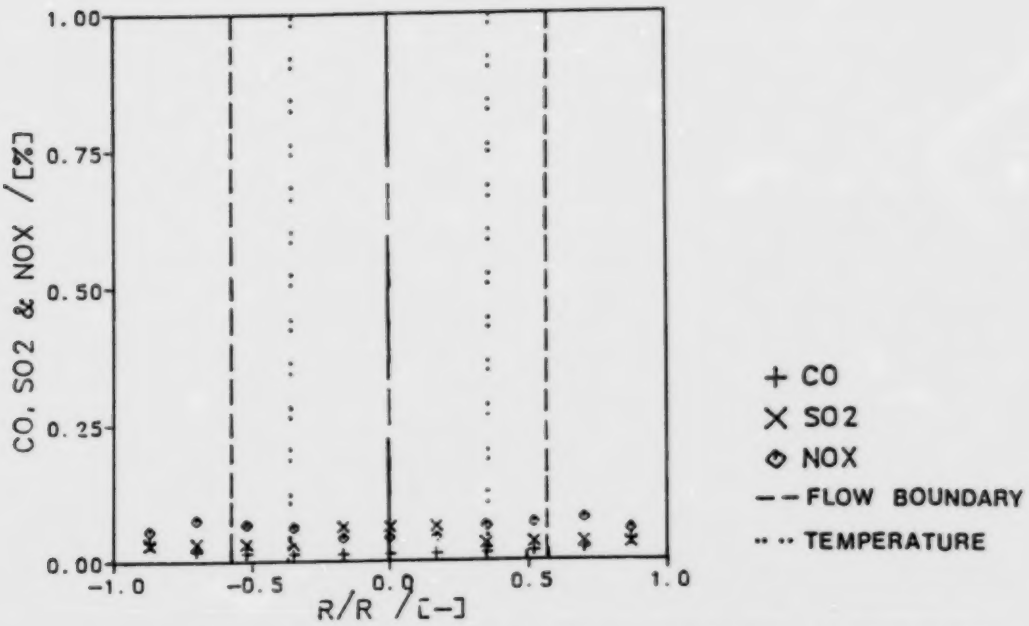


Fig. 4.46: Radial Variation of CO, SO_2 and NO_x for Test 4; Z/L = 0.35

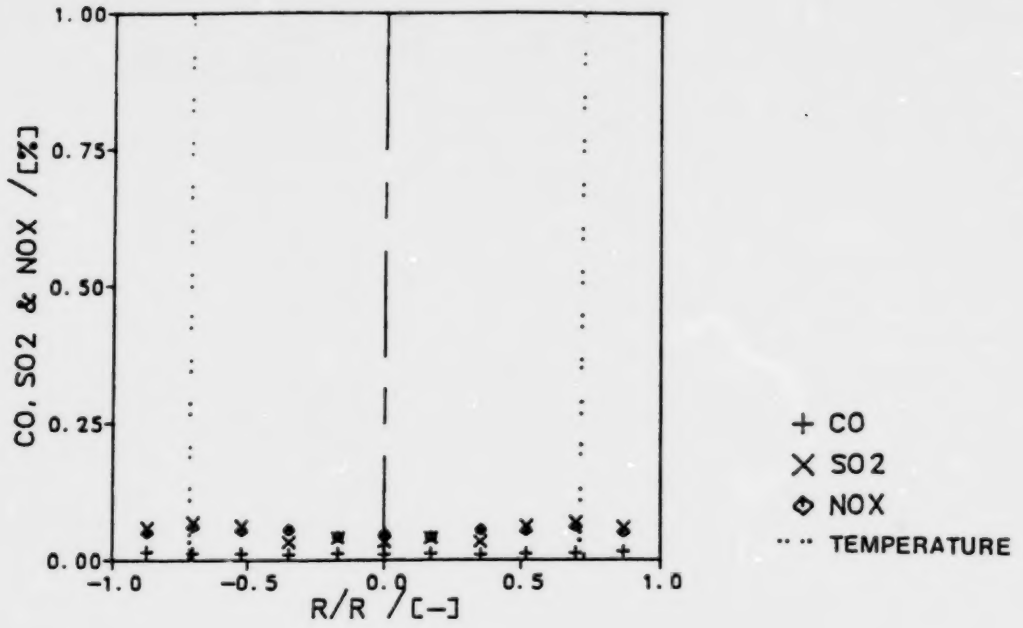


Fig. 4.47: Radial Variation of CO, SO_2 and NO_x for Test 4; Z/L = 0.53

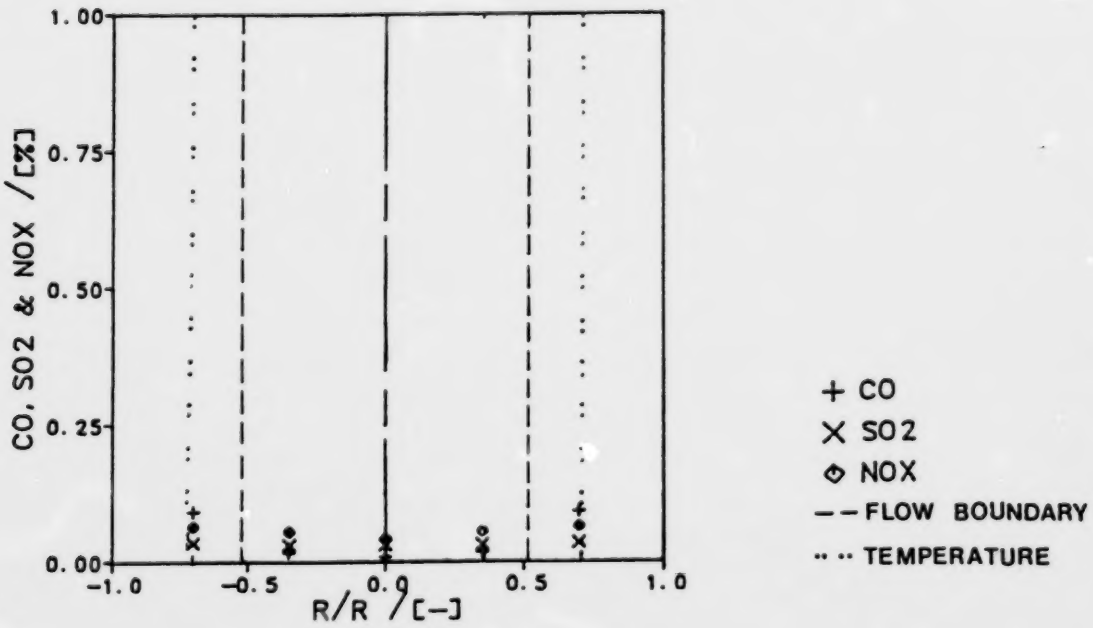


Fig. 4.48: Radial Variation of CO, SO_2 and NO_x for Test 5; Z/L = 0.35

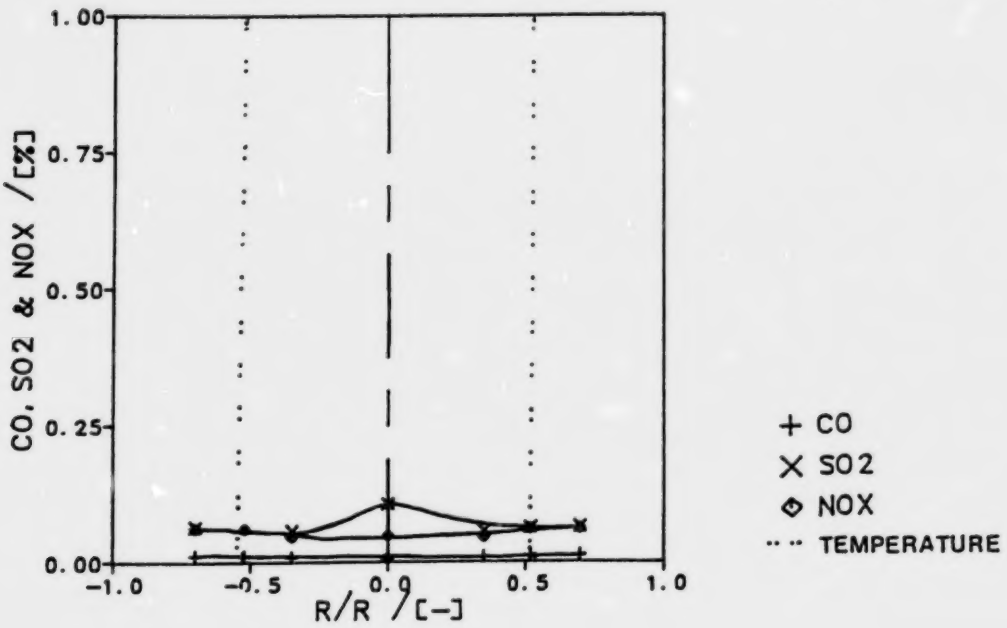


Fig. 4.49: Radial Variation of CO, SO_2 and NO_x for Test 5; Z/L = 0.53

4.4 Particulate sampling and analysis

Particulate samples collected (refer to Table 2.10) were analysed and the results are presented in Tables 4.24 and 4.25

Table 4.24: Particulate analysis data

Sample #	Concentration gm^{-3} at 15°C	Ultimate Analysis %C	%H	%N	(S+O)	Proximate Analysis % Moisture	% %C	% Vol.Matter	Ash	% Carbon burnout-Bortz[7]
P.1.1	86.19	0.47	2.96	2.28	94.29	1.6	95.20	1.6	1.6	98.77
P.1.2	98.56	0.13	0.87	0.06	98.94	1.0	97.00	1.0	1.0	98.02
P.2.1	71.48	0.31	2.05	0.81	96.83		insufficient sample			-
P.2.2	107.05	0.28	3.22	0.11	96.39	1.6	95.20	1.6	1.6	98.77
P.3.1	59.09	0.37	32.91	0.54	66.18	4.57	0	39.23	56.20	98.84
P.3.2	288.00	1.06	70.07	0.78	28.09	2.28	0	71.10	26.62	95.89
P.3.3	254.29	1.10	62.57	0.60	35.73	2.30	0	67.70	30.00	96.52
P.3.4	303.33	1.26	65.74	0.66	32.34	2.30	0	72.20	25.50	95.64
P.3.5	322.00	1.09	64.48	0.60	33.83	2.30	0	72.20	25.50	95.64
P.3.6	332.00	1.35	78.00	1.39	19.26	2.30	0	86.50	11.20	88.17
P.4.2	146.25	1.43	67.77	1.20	29.60	3.45	0	69.80	26.75	95.91
P.4.1	145.00	0.97	39.93	0.74	58.36	3.45	0	45.80	50.75	98.55
P.4.3	258.33	1.32	63.41	1.06	34.21	2.30	0	69.45	28.25	96.21
P.4.4	235.00	1.32	66.07	0.84	31.77	2.30	0	73.95	23.75	95.21
P.4.5	260.00	1.50	64.57	0.85	33.08	3.45	0	74.05	22.50	94.86
P.4.6	220.00	1.39	63.71	1.09	33.81	3.45	0	74.05	22.50	94.86
P.5.1	100.00	0.90	64.11	0.73	34.26	4.60	0	56.70	38.70	97.64
P.5.2	338.51	1.43	72.53	0.99	25.05	4.60	0	77.00	18.40	93.38
P.5.3	421.67	1.59	81.02	1.06	16.33	5.75	0	83.00	11.25	88.23

Table 4.25: Carbon burnout calculations

Test	Loc.	T_x[a] (Bortz et al.) %	T_{CO2}[b] (STM, B&W) %	Fuel
1	Br	98.77	99.44	H.O.
	3b	98.02	99.57	5%E.O_2
2	Br	-	96.84	H.O.
	3b	98.77	97.93	5%E.O_2
3	Br	98.84	94.67	CWM
	5b	95.89	94.92	3%E.O_2
	4b	96.52	95.20	
	3b	95.64	95.02	
	2b	95.64	93.73	
	1b	88.17	95.28	
4	Br	95.91	95.76	CWM
	5b	98.55	96.65	5%E.O_2
	4b	96.21	95.56	
	3b	95.21	95.40	
	2b	94.86	93.62	
	1b	94.86	93.45	
5	Br	97.64	97.04	CWM
	4b	93.38	96.89	5%E.O_2
	2b	88.23	91.77	STM.

(a) T_x = carbon burnout based on Bortz[7]
(b) T_{CO2} = carbon burnout based on CO_2 concentration in the flue

4.5 Heat flux profiles

The heat flux to the furnace walls, both total and radiative is presented in the following Tables 4.25 to 4.29 for each of the tests 1 through 5. Diagrams showing the axial profiles of the heat flux are presented in Figs 4.50 to 4.54. The furnace load in the water cooling jackets for each test is given in Table 4.30 and plotted in Figs 4.55 to 4.59 as heat flux removed against Z/L.

Table 4.26: Heat flux to furnace walls for Test No. 1

Z/L /[-]	Q_{TOT} /[kWm^{-2}]	Q_{RAD} /[kWm^{-2}]
0.13	143.4	74.0
0.22	217.	103.4
0.32	181.8	75.6
0.41	145.3	60.7
0.51	129.2	42.2
0.60	109.7	53.0
0.70	115.3	46.8
0.78	112.1	34.8
0.86	106.9	27.0
0.94	85.0	24.5

Table 4.27: Heat flux to furnace walls for Test No. 2

Z/L /[-]	Q_{TOT} /[kWm^{-2}]	Q_{RAD} /[kWm^{-2}]
0.13	124.6	70.5
0.22	201.5	116.3
0.32	171.1	71.1
0.41	128.3	75.2
0.51	110.6	38.0
0.60	93.2	23.9
0.70	88.6	23.9
90.78	88.6	23.9
0.86	95.9	20.2
0.94	95.9	27.0

Table 4.28: Heat flux to furnace walls for Test No. 3

Z/L /[-]	Q_{TOT} /[kWm^{-2}]	Q_{RAD} /[kWm^{-2}]
0.12	124.6	56.8
0.21	207.4	88.2
0.31	197.5	81.1
0.40	175.0	80.3
0.50	148.1	67.5
0.59	136.8	64.2
0.70	124.6	56.8
0.77	117.1	56.0
0.86	117.1	48.3
0.94	106.0	43.7

Table 4.29: Heat flux to furnace walls for Test No. 4

Z/L /[-]	Q_{TOT} /[kWm^{-2}]	Q_{RAD} /[kWm^{-2}]
0.12	78.7	40.7
0.21	155.7	55.3
0.31	174.0	66.9
0.40	158.6	59.9
0.50	129.2	54.1
0.59	127.4	51.0
0.70	118.0	45.3
0.77	111.9	44.5
0.86	102.3	39.9
0.94	91.4	38.4

Table 4.30: Heat flux to furnace walls for Test No. 5

Z/L /[-]	Q_{TOT} /[kWm^{-2}]	Q_{RAD} /[kWm^{-2}]
0.12	119.0	34.9
0.21	121.8	33.0
0.31	147.7	56.8
0.40	132.1	65.0
0.50	114.3	56.8
0.59	102.3	54.1
0.70	114.3	48.3
0.77	118.0	46.9
0.86	114.7	50.3
0.94	98.8	41.8

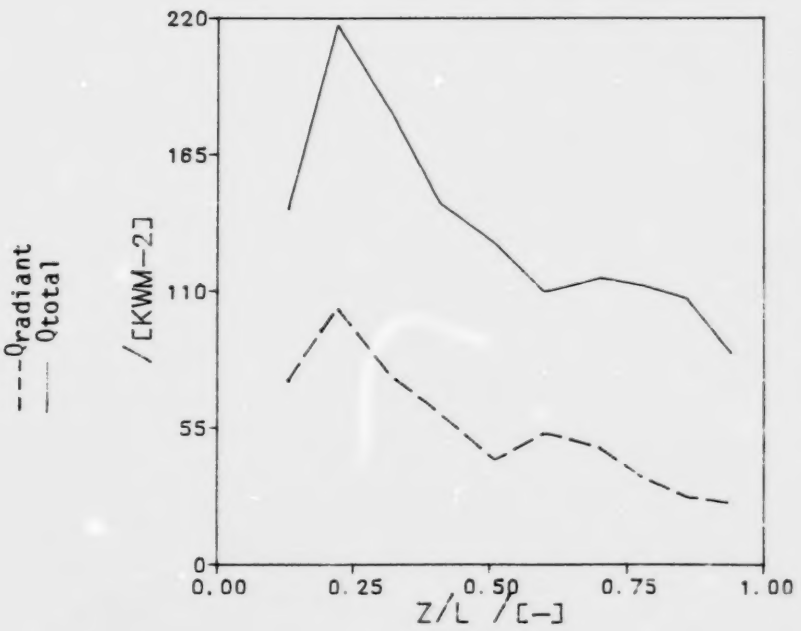


Fig. 4.51: Heat flux to furnace walls for test 1

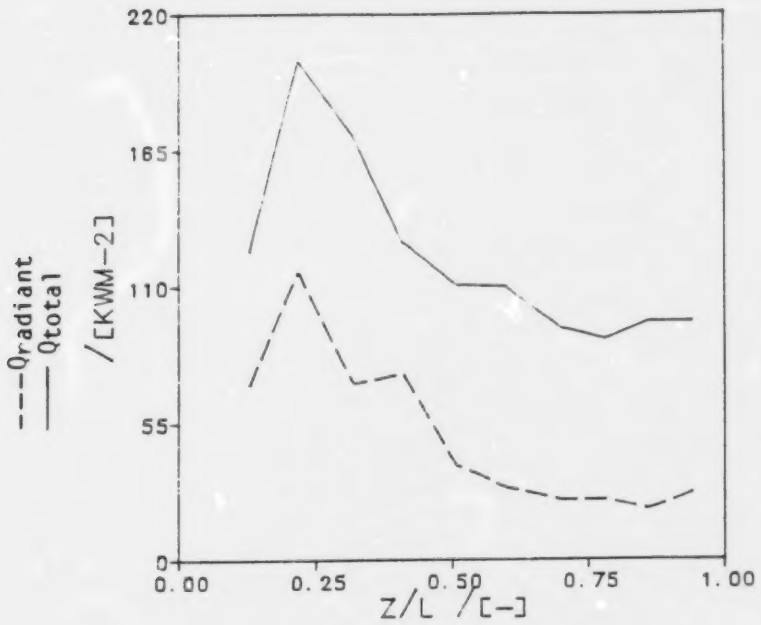


Fig. 4.52: Heat flux for furnace walls for test 2

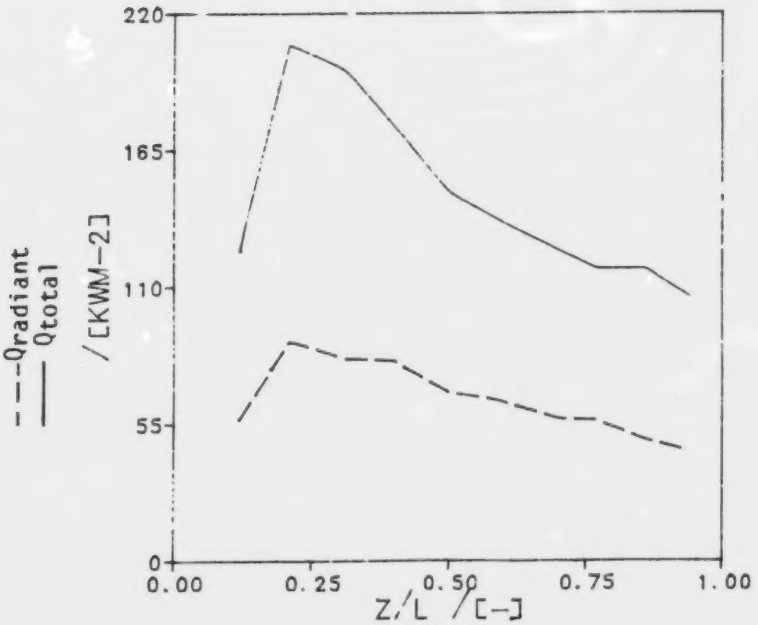


Fig. 4.53: Heat flux for furnace walls for test 3

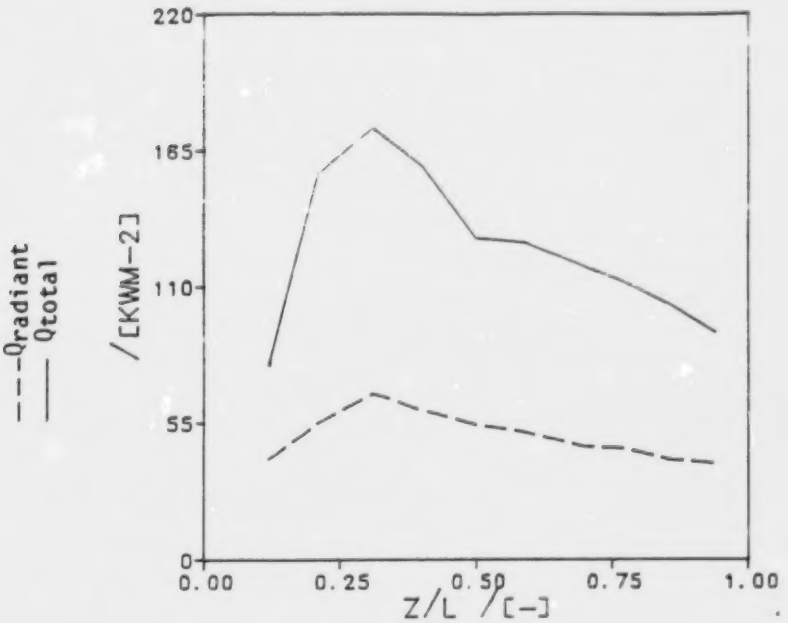


Fig. 4.54: Heat flux for furnace walls for test 4

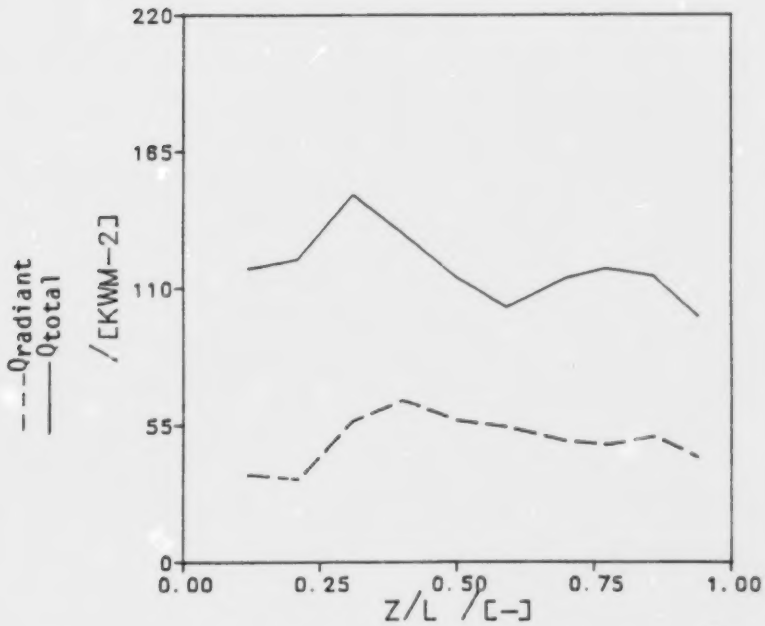


Fig. 4.55: Heat flux for furnace walls for test 5

Table 4.31: Heat flux removed by furnace cooling sections

Test No.	Section	Furnace load /[kWm-2] 1	2	3	4	5
1		58	66	40	36	31
2		67	66	49	31	31
3		71	66	63	52	31
4		54	52	54	47	42
5		54	57	58	42	46

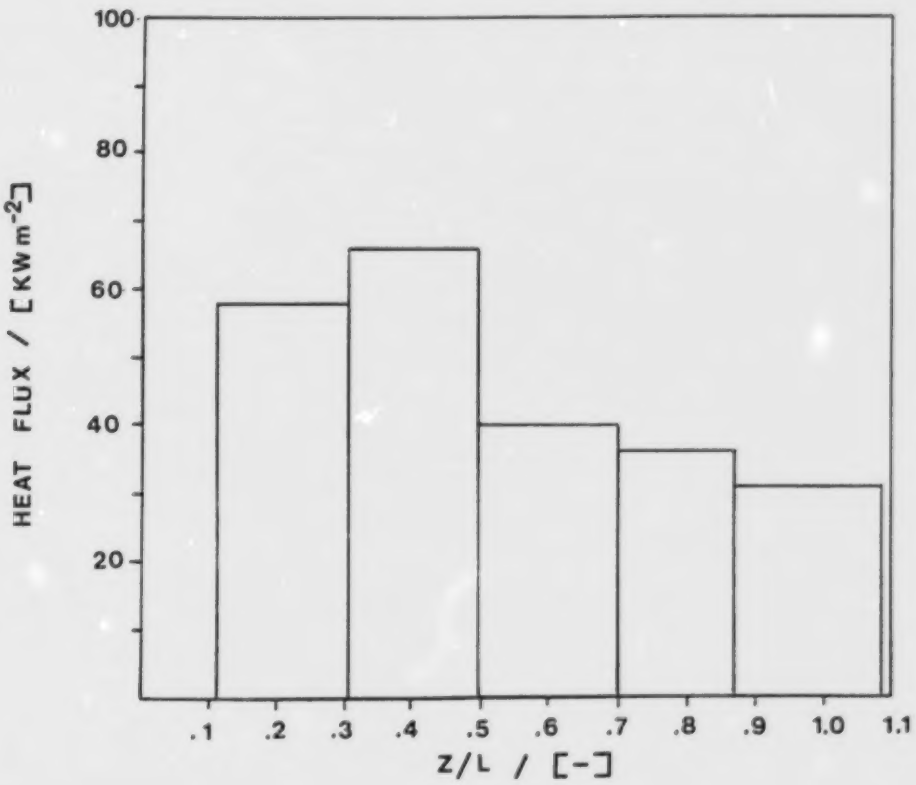


Fig. 4.55: Heat flux removed along Z/L for test 1

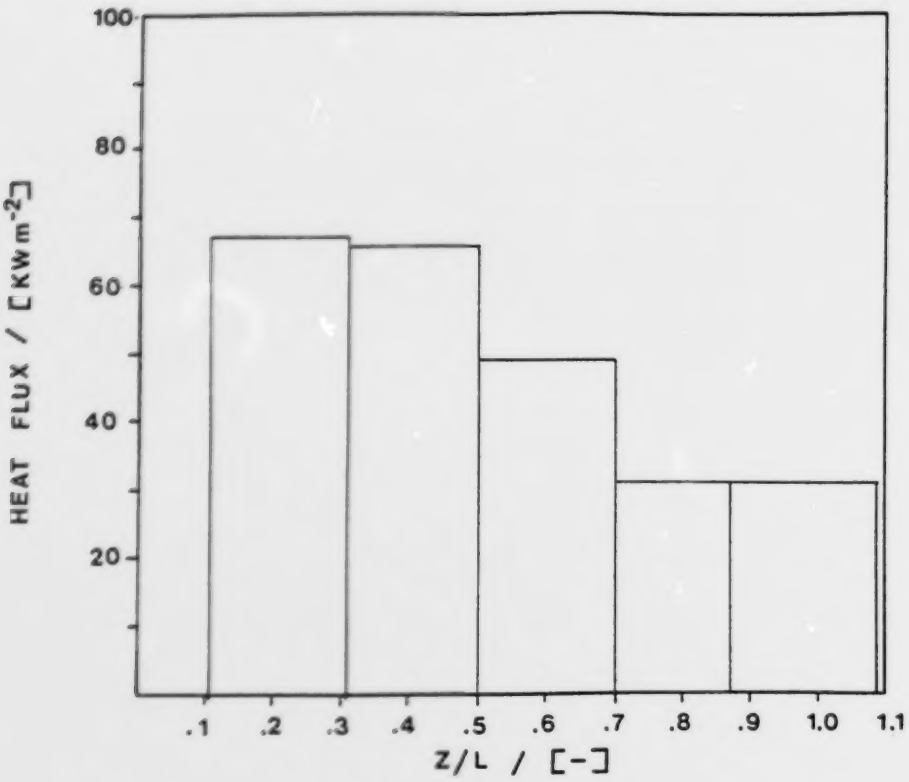


Fig. 4.56: Heat flux removed along Z/L for Test 2

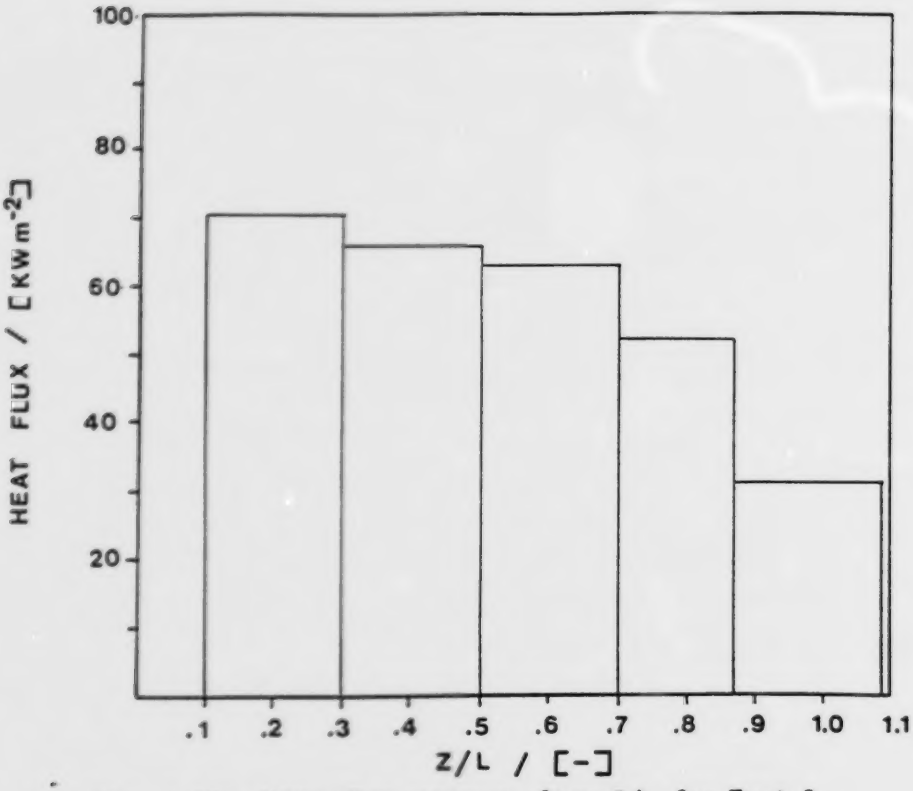


Fig. 4.57: Heat flux removed along Z/L for Test 3

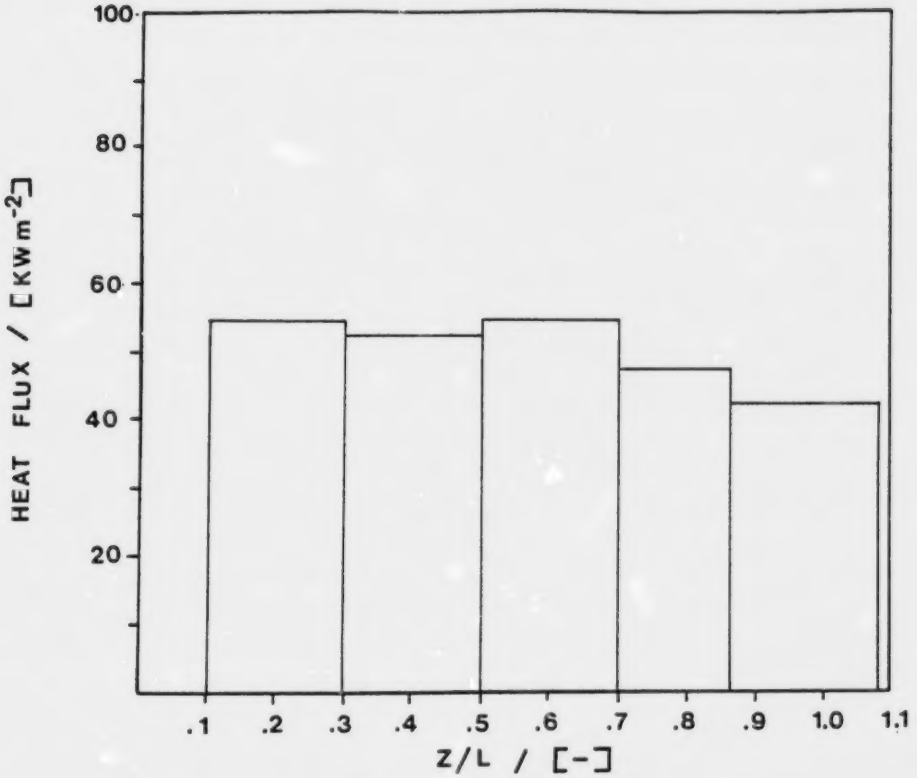


Fig. 4.58: Heat flux removed along Z/L for Test 4

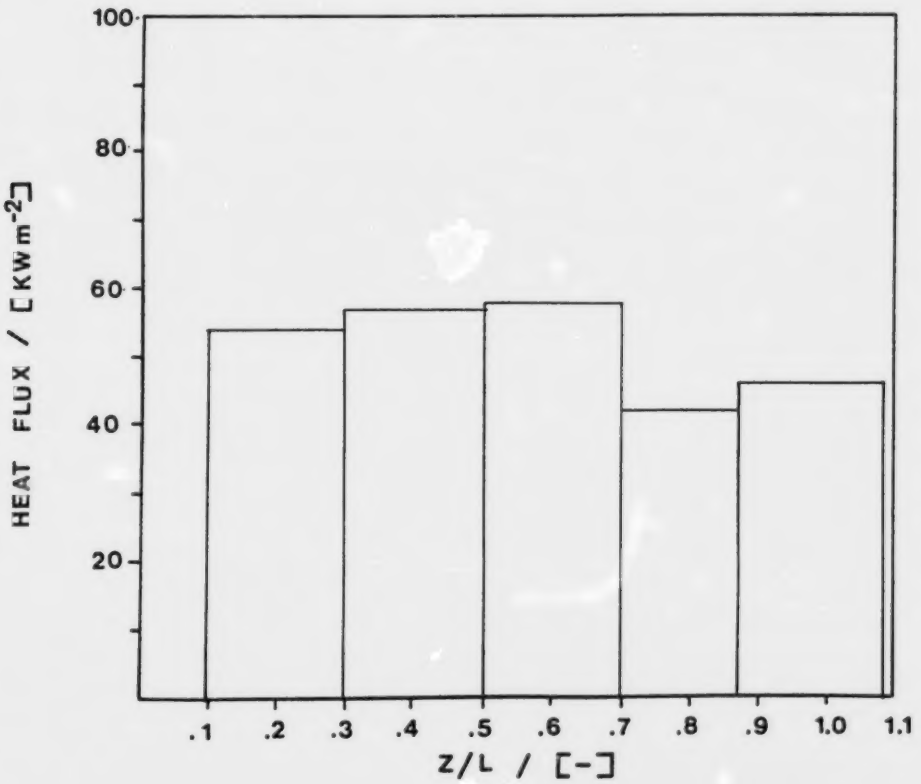


Fig. 4.59: Heat Flux removed along Z/L for Test 5

4.6 Fuel and ash analyses

The fuel samples collected (refer to Table 2.3) were analysed and the results appear in Table 4.31. Ash samples collected (refer to Table 2.11) were analysed and the results appear in Table 4.32.

Table 4:32: Fuel analysis data

Sample #	Fuel Type	Ultimate Analysis %C	%H	%N	%S	%O	C.C.V.* kJkg-1	Solids %	Moisture %	Viscosity
F.1.1	HFO	77.50	9.40	0.52	2.38	10.20	42691	--	2.4	--
F.1.2	HFO	87.58	11.60	0.56	2.21		42817	--	2.1	--
F.2.1	HFO	85.06	10.82	0.46	2.12	1.54	42893	--	2.4	--
F.3.1	CW	--	--	--	--	--	--	69.7	30.3	--
F.3.2	CW	--	--	--	--	--	--	69.8	30.2	--
F.3.3	CW	--	--	--	--	--	--	70.6	29.4	--
F.3.4	CW	--	--	--	--	--	--	70.9	29.1	--
F.3.5	CW	--	--	--	--	--	--	71.1	28.9	--
F.3.6	CW	--	--	--	0.80	--	25225	70.8	29.2	--
F.3.7	CW	--	--	--	--	--	--	70.3	29.7	--
F.4.1	CW	--	--	--	--	--	--	70.3	29.7	--
F.4.2	CW	--	--	--	--	--	--	70.1	29.9	--
F.4.3	CW	--	--	--	--	--	--	70.3	29.7	--
F.4.4	CW	--	--	--	--	--	--	70.6	29.4	--
F.5.1	CW	--	--	--	--	--	--	69.7	30.3	--
F.5.2	CW	--	--	--	--	--	--	69.5	30.5	--

Table 4.33: Ash analysis data

Sample		Ultimate Analysis %C	%H	%N
A.3.1	CW	65.81	0.60	1.36
A.3.2	CW	82.96	0.88	1.70
A.4.1	CW	87.62	0.91	1.76
A.4.2	CW	54.16	0.49	1.40
A.4.3	CW	63.68	0.51	1.39

*CCV = Net corrected calorific value

4.7 Flame emissivity

Several attempts were made to measure the flame emissivity at points along the combustion chamber axis. However, the results obtained revealed that instrumentation with a higher capability of noise shielding was required. Due to the time required to diagnose the problem and procure such instrumentation, it was not possible to measure the flame emissivity during this study.

5. DISCUSSION OF RESULTS

Tests 1 through 5 were conducted following modification of the throat geometry as described in section 3.3. Each division appearing in Results (sections 4.1 to 4.6) is discussed under similar corresponding headings as follows.

5.1 Flow boundaries

Flow boundary mapping in a turbulent non-isothermal flow is a measurement which is subject to only a moderate degree of repeatability. Measurements made in this study should be considered subject to an estimated minimum uncertainty of ±25 mm along the radius. Great care was taken during the tests to protect against entrainment of tramp air and to repeat boundary detection in order to verify the position measurement. An examination of both the inside and outside of the detected flow boundary was made in search of a second reversal point. However, none was found. The trends in the actual flow boundary maps are difficult to predict since the strength of the boundaries in this non-isothermal flow are dependent on fuel reactivity, the onset of combustion, the spray angle and swirl number. The recirculation flow boundaries shown in Figs 4.1 through 4.5 exhibit a type B flame. All boundaries begin outside the spray angle of the nozzle and curve inward across the angle to close the recirculation envelope.

In the case of test No. 2, the zone appears to expand again slightly before closing in toward the centreline of the combustion chamber. Comparing Test No. 2 (steam atomised HFO) with Test No. 5 (steam atomised CW) reveals

that no expansion at the tip of the recirculation zone occurs as was the case with oil. In general, a CW flame exhibits a smaller recirculation zone than a HFO flame.

5.2 Flame temperature profiles

The standard procedure used in in-flame temperature profiling at CES is a measurement of the peak temperature at each of 30 grid locations in the combustion chamber. The grid consists of 5 axial locations (at 600 mm intervals) along the combustion chamber, each containing 6 radial locations (at 100 mm intervals) beginning at the centreline. A major source of uncertainty arises from the assumption that such a grid should reveal the position of peak temperatures. While a trend certainly will be indicated, the actual position of maximum in-flame temperatures cannot be assumed to lie on the grid. Hence a peak temperature could occur up to an estimated 75 mm on either side of the radial grid point at which the peak temperature was detected. Also, a larger number of axial sampling locations could reveal a slightly different axial peak flame temperature profile. The axial flame temperature profiles are shown in Figs 4.6 through 4.10.

Test No. 1 (5% O_2, HFO) shows a higher peak than Test No. 2 (5% O_2, steam, HFO), due mainly to the difference in atomisation mediums - air in Test No. 1 and steam in Test No. 2. Atomising with steam appears to produce a slightly cooler oil flame.

Test No. 3 (3% O_2, CW) shows a higher axial flame temperature than Test No. 4 (5% O_2, CW). These initially higher flame temperatures in Test No. 3 are due to lower thermal inertia and longer residence time (demonstrated in

staged combustion) while back-end temperatures are higher in Test No. 4 since the char particles require a longer length for combustion (increased residence time). This also explains why back-end temperatures are higher in a CW flame than those observed in an oil flame. The higher initial flame temperatures for oil are caused mainly by higher fuel reactivity when compared to coal.

Test No. 5 (5% O_2, steam, CW) shows a much lower peak than either of the other two coal water tests with the peak occuring further downstream (Port 2 compared with Port 1 in Tests 3 and 4). This may indicate that a lack of oxygen in the atomisation medium retards ignition of the CW flame, shortening required combustion residence time.

The radial temperature profiles for each test are given in Figs 4.11 through 4.15. The radial location of the flow boundary position is superimposed on these profiles to indicate where the flow boundaries lie in relation to the peak radial temperatures measured. In Tests 1, 2 and 3, peak temperature locations lie inside their respective flow boundaries. The average distance from the temperature peaks to the flow boundaries is 83 mm with a standard deviation of ±41.8 mm. In view of the uncertainty introduced by the actual measuring of recirculation zones and flame temperatures, relatively good correlation can be assumed between the flame temperature profiles and the flow boundary locations.

Tests 4 and 5 together exhibit an average distance of 138 mm ± 29 mm from the temperature peaks to the flow boundaries and a slightly more deviant trend is observed. In Test 4, the measured peak temperature at the forward axial location lies 160 mm inside the recirculation zone while at the second axial location this distance is reduced to 130 mm. Test 5 indicates a similar trend in the forward peak temperature location (160 mm inside the zone) but at the

second axial location, the peak temperature lies 100 mm outside the recirculation zone. The uncertainty in the measurements accounts for a portion of this seemingly large deviation.

5.3 Gas profiles

The axial O_2 and CO_2 concentration profiles shown in Figs 4.16 to 4.20 reveal that an oil flame exhibits an initially lower O_2 concentration than a coal water flame. The O_2 increases to a maximum about halfway down the combustion chamber. The initially higher O_2 level in the coal water flame begins to decline rapidly at the same axial position, about halfway down the combustion chamber. This is a result of fuel reactivity and the onset of combustion (heavy fuel oil being more highly reactive than the coal water fuel).

Comparing Figs 4.18 to 4.20 reveals a similar trend in the axial O_2/CO_2 profile for each case. However, as the excess O_2 is increased from 3% to 5%, the O_2 concentration along the axis is also increased. In the case of steam atomisation (Fig 4.20) the O_2 level is much higher initially, indicating a delay in the onset of combusiton due to steam atomisation.

Axial variations of CO, SO_2 and NO_x shown in Figs 4.21 to 4.25 reveal overall lower CO and SO_2 and higher NO_x emissions in a CW flame than a HFO flame. A comparison of the coal water tests (Test Nos. 3 to 5, Figs 4.23 to 4.25) reveals little change except in the concentration of SO_2.

Generally consistent radial profiles of oxygen and carbon dioxide are observed in Tests 1 to 4. Test 5 (Fig 4.36) exhibits a different pattern in port 1 with a gradual drop in O_2 concentration. The radial profiles shown in Figs 4.26 to 4.37 also enable a comparison of peak flame temperature and flow

boundary location. At axial positions near the burner, combustion takes place at radial positions corresponding to the temperature peaks. Good correlation is shown between the peak flame temperature location and radial positions of lowest O_2 concentration. Test No. 4 (Figs 4.33 and 4.34) and Test No. 5 (Fig 4.36) show peak temperatures that do not correspond with minimum O_2 levels. All $O_2/CO_2/CO$ measurements recorded in Tables 4.6 to 4.23 were plotted on a dry f'ue gas volumetric combustion chart (see Appendix III, Fig 1) as a theoretical check on the accuracy of these gas compositon measurements. Gas concentrations in the HFO flames of Tests 1 and 2 fell on the model stoichoimetric line. Points plotted from CW flame data fell slightly off to one side of this curve, the askewedness being an indication of carbon loss in the coal water flame. The gas data from ports 1 and 2 displayed the greatest amount of askewedness which is reasonable to expect with more carbon being present in the CW flame nearer the atomiser. It would appear that no unreasonable errors exist in the gas data. It is possible that, as discussed in section 5.2, the flame temperature peaks do not lie on the grid points where measurements were made. This could shift the peak temperature location closer to the flow boundaries and minimun O_2 points in Figs 4.34 and 4.36.

5.4 Particulate analysis

Stoichiometric combustion calculations were made and are presented in Appendix VIII. Carbon burnout was calculated using the formulae reported by Bortz[7] and this compared very well with the burnout calculated from the CO_2 in the flue; the maximum deviation being 4%. This implies that carbon burnout can be predicted from the CO_2 concentration in the flue.

5.5 Heat flux profiles

Table 5 summarises the peak heat flux data and the ratio of Q_{rad}/Q_{tot} for all the tests.

Table 5.1 Summary of heat flux data

Test No.	Maximum Values/[kWm^{-2}] Q_{tot}	Q_{rad}	Q_{rad}/Q_{tot} /[-]	Z/L /[-]
1	217.4	103.4	0.48	0.22
2	201.5	116.3	0.58	0.22
3	207.4	88.2	0.43	0.21
4	174.0	66.9	0.38	0.31
5	147.7	65.0	These do not occur at the same value of Z/L	

A comparison of Tests 1 and 4 (see Figures 4.50 and 4.53) show that, with 5% excess oxygen and air atomisation, the heat flux profiles are similar in shape. However, the peak heat release rate is displaced further downstream from the burner for a CW flame than for a HFO flame. In addition the maximum heat fluxes are considerably lower for the CW flame as is the maximum flame temperature.

The axial displacement of the peak heat release rates is mainly due to the difference in fuel reactivities between coal water and heavy fuel oil. There may also be a minor effect from the change in spray angles (60° for HFO and 50° for CW).

A comparison of Figs 4.50 to 4.54 with Figs 4.55 to 4.59 show the relation between measurements of heat flux from the flame to the furnace walls and heat removed from the furnace walls by the cooling water. The flame heat flux decreases less steeply down the combustion chamber in a CW flame than in a HFO flame. A similar trend appears in the heat flux removed from the furnace wall with a slightly higher load being removed at the back end of the combustion chamber in CW flames than in oil flames. Higher back end flame temperatures and flame heat flux values are the cause.

The radiant heat flux peaks are lower in the coal-water flames than in the oil flames with the peak locations displaced further downstream in the CW flames. Differences in fuel reactivity are mainly responsible for this shift. Particle size may also contribute some effect.

The axial disposition of the heat release is important in determining the relative heat absorption of front and rear walls of a boiler and the magnitude of the peak heat fluxes on the burners and adjacent walls where waterside dry-out may be a problem.

6. CONCLUSIONS

The following conclusions have been drawn from an evaluation of the data presented in section 4.

1) The NRCC Variable Geometry CLM Nozzle used during this series of tests proved that it was capable of firing both HFO and CW fuels with atomisation air/fuel ratios in the range 0.23 to 0.42.

2) For a divergent refractory throat with a half angle of 35° and $1.0 \leq L/D \leq 1.5$ a stable type B flame is achieved with: (a) HFO using a 60° spray angle; and (b) CW using a 50° spray angle.

3) A coal water flame produces a smaller recirculation zone than a heavy fuel oil flame of the same nominal thermal input and excess oxygen.

4) The axial temperature profiles of coal water and corresponding heavy fuel oil flames are similar in shape.

5) The peak temperature is higher and occurs closer to the atomiser in a heavy fuel oil flame than in a corresponding coal water flame.

6) Back-end temperatures in a coal water flame are higher than in a corresponding oil flame.

7) Oxygen concentration is initially lower in an oil flame than in a comparable coal water flame while lower CO and SO_2 and higher NO_x emissions are exhibited in a CW flame.

8) The high values of carbon burnout proved that the nozzle was atomising well. The carbon burnout in the breeching compares very well with the burnout calculated from the CO_2 concentration in the flue with corrections made for propane combustion.

9) The ratio of Q_{rad}/Q_{TOT} is higher for a steam atomized flame than for an air atomized flame using HFO. With CW, however, the maximum values of heat flux do not occur at the same value of Z/L, therefore, a ratio cannot be determined.

10) Similar trends are visible in the heat flux characteristics when comparing air and steam atomised HFO flames. There was a tendency for the heat flux with air atomised flames to increase toward the end of the combustion chamber before it decreased to its final value. However, with steam atomisation, the heat flux dropped and then increased to its final value.

11) For the CW tests, the air atomised 3% excess O_2 had higher values of heat flux than the test with 5% excess O_2 air atomised. However, the same general trend was witnessed with these two. The steam atomised test showed a more constant value of heat flux than the other two tests of this series.

12) The steam atomised HFO showed a much higher peak heat release rate than that with CW.

13) The 5% excess oxygen HFO test showed higher values of heat flux than

the CW test close to the burner. Toward the end of the combustion chamber though, the heat flux for both tests were comparable.

14) The flame heat flux decreases less steeply down the combustion chamber in a CW flame than in a HFO flame.

15) Although the tests were of a short duration, no erosion of the atomiser components was observed.

RECOMMENDATIONS

1) In view of the data obtained during the present study, plans and preparations for a large scale, long term burn of CW fuel, should begin.

2) A long term test of the NRCC nozzle burning CW fuel should be made to generate quantitative information on nozzle wear or erosion. In so far as the NRCC nozzle has been designated for use in a study "To Determine the Optimum Ash Level of Coal Water Fuels For Use In Utility Boilers" which will involve 2000 hours of continuous burning in the CES combustion test facility such data will be obtained.

3) This study produced data on one nozzle and one coal water fuel. A data bank on other candidate fuels and nozzles should be built up in order to provide engineers with ready access to the most up to date technological information on burning coal water fuels. This can be done through a program of selective (short term) combustion tests.

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APPENDIX I:

CES Combustion Test Facility

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1. General

The Centre for Energy Studies (CES) was formed at the Technical University of Nova Scotia (TUNS) in 1978. The objectives of the Centre are to promote education, research, and development in energy related fields. The area of combustion has been given a high priority. A flame tunnel was installed in 1982 and since that time has been continually modified and upgraded.

The use of coal as a substitute for imported heavy fuel oil has been given a high priority by the Canadian Federal Government. Coal-liquid mixtures appear to be a viable substitute for residual fuel oil. Modifications to the flame tunnel and the installation of a slurry handling system enable combustion and heat transfer characteristics of slurry flames to be studied.

2. Flame tunnel and ancillary equipment

A schematic diagram of the flame tunnel is shown in Figure 1. The forced draught (FD) fan is capable of delivering between 0.48 and 1.90 m^3s^{-1} of combustion air up to a static pressure of 26.90 kPa. The air flow rate is controlled by an electrically operated air damper and measured by noting the pressure drop across an orifice plate.

A steam heat exchanger provides the first stage of air preheat up to 121°C and a direct-fired propane air preheater boosts the temperature up to 288°C. The propane burner is mounted axially in the combustion air duct and thus vitiates the air: the oxygen concentration of the air at the windbox is reduced to about 19%. A variable vane air register within the windbox at

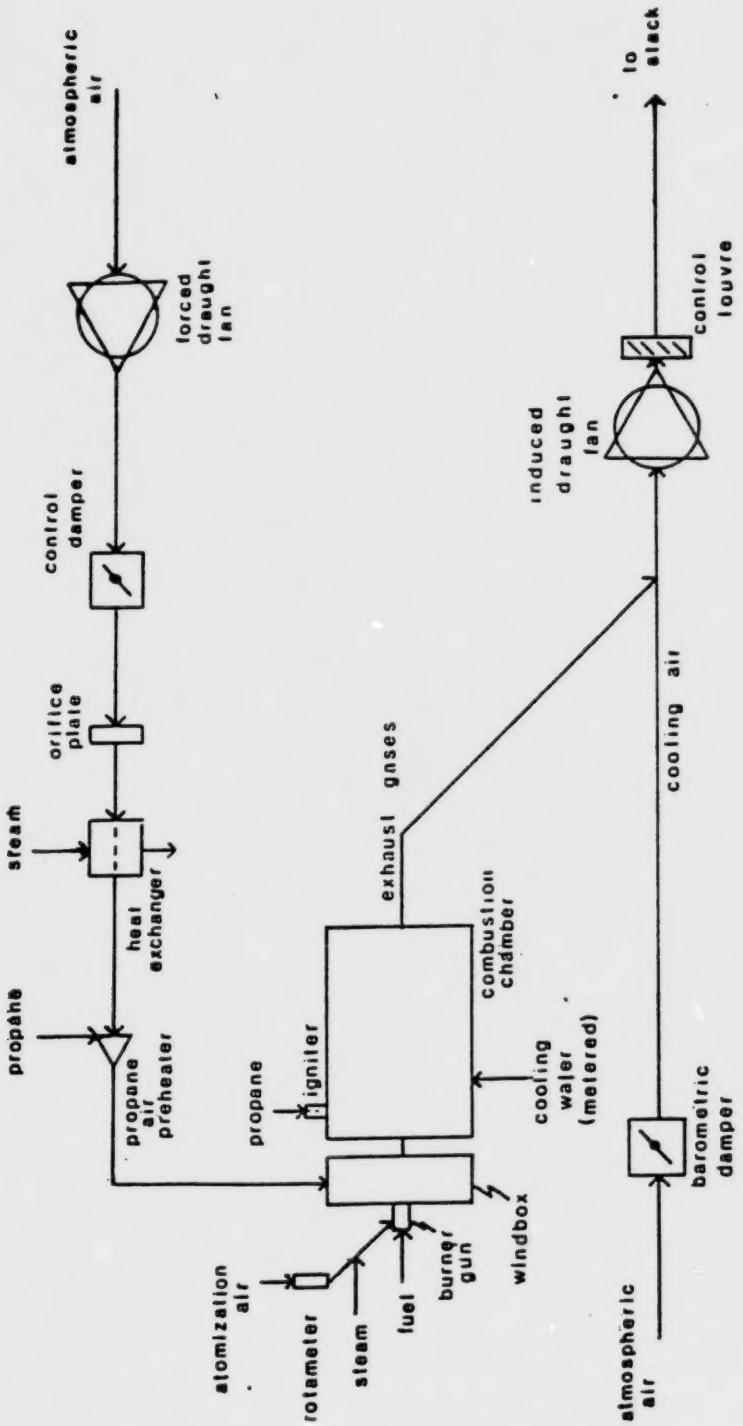

Figure 1: Schematic diagram of the flame tunnel

the burner throat allows a full range of combustion air swirl adjustment.

The combustion chamber section constructed of 19 mm thick mild steel, is 3 m long and 1.22 m diameter. When the tunnel was first installed the combustion chamber was completely lined with high temperature refractory bricks. Subsequently, a large portion of the refractory lining has been removed to simulate load conditions. The refractory throat, front and rear walls, and a hearth covering 45% of the combustion chamber floor as protection against slag attack, has been retained. The outside of the combustion chamber is water-jacketed with five independently controlled sections each with the capability of measuring the flow rate and inlet and outlet temperatures of the cooling water.

Five large access ports along each side of the combustion chamber, and one in the breeching section, allow visual observation of the flame. These ports also serve as openings through which any of a number of in-flame measurement probes can be inserted. A large viewport located at the rear end of the furnace exit breeching enables an unobstructed axial view of the flame: a video camera placed at this point allows the operator to observe the flame on a video monitor and record it on video tape. Communication among workers during testing is made possible through the use of FM transceivers installed in conventional high quality ear protectors. Comments can also be recorded on the video tape using these headsets.

The hot combustion products leave the combustion chamber through a 0.4 m diameter refractory lined breeching section which is water-jacketed up to just before the induced draught (ID) fan. At the furnace exit, within the breeching, is a large observation port and a tee section: the tee section can house slagging/fouling or erosion/corrosion probes. The observation

port enables photographs of these probes throughout the duration of a test as well as insertion of measurement probes.

The gas temperature at the inlet to the ID fan is controlled by allowing ambient air to be drawn in through a temperature controlled damper so as the temperature never exceeds 400°C. The ID and FD fans act as a balanced draught system and control the furnace pressure. It is necessary to maintain a slightly negative pressure within the furnace to avoid the efflux of hot gases when the ports are opened. The flue gases are exhausted from the ID fan into a brick stack.

3. Heavy fuel oil storage and burner delivery system

For the burning of heavy fuel oil, a conventional fuel handling system, shown in Figure 2, is used. It consists of a 4500 dm^3 heated storage tank, pump and both steam and electric heat exchangers to preheat the fuel up to 105°C. Fuel lines are connected to the burner gun in such a way as to enable switching from one fuel to another with no interruption in burning. A propane igniter is used to ignite the fuel atomised by the burner gun and nozzle.

4. Slurry handling and burner delivery system.

A schematic diagram of the slurry handling system is shown in Figure 3. Fuel, if delivered in barrels, is loaded into a 1 m^3 transfer tank, shown as T_1 in Figure 3, from where it is pumped to the 3 m^3 holding tank (T_2) through a 50.8 mm. line. A Viking gear pump driven by a 3.73 kW (5 Hp) motor is used. The 3m^3 tank contains a copper coil enabling preheating of

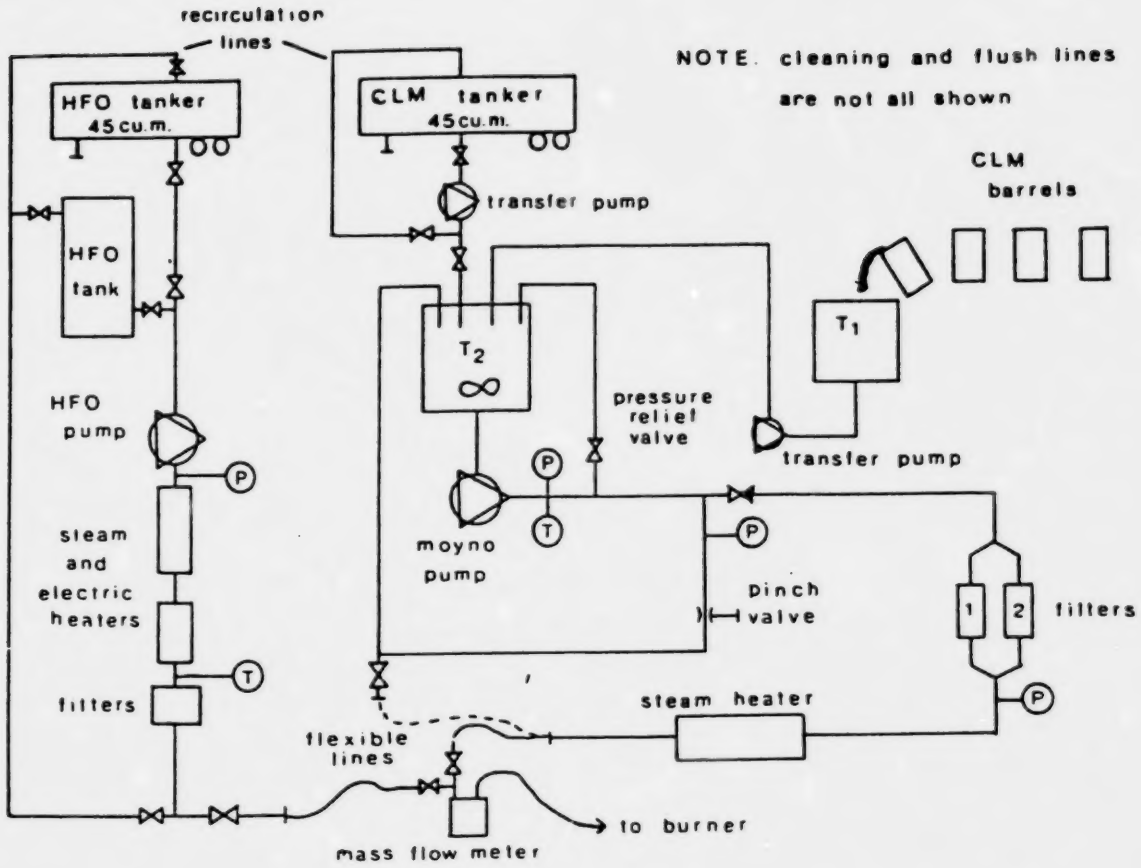

Fig. 2: Fuel Handling and Burner Delivery System

stored fuel which improves handling of coal-oil-water (COW) slurries. A Lightning mixer is mounted in the holding tank and is used to agitate the fuel to prevent settling. For coal-water slurries the heating coil can be switched to a cooling coil which is needed to keep the temperature down which rises as a result of recirculation. If the slurry is delivered in a tanker, it can be transferred to the 3 m^3 tank by means of a smaller Moyno pump and recirculated back to the road tanker.

A Moyno variable speed progressive cavity pump with a capacity of 0.88dm^3s^{-1} at pressures up to 4.1 MPa is used to deliver the fuel to the burner gun. Fuel pressure is controlled by allowing the slurry to return to the holding tank through a 25 mm recirculation line. A pinch valve, shown in Figure 3, is located on this recirculation line. By carefully adjusting both pump speed and the pinch valve any desired pressure and fuel flow rate can be achieved at the gun.

Fuel which does not recirculate to the holding tank passes through a filter, mass flow meter and heat exchanger before being delivered to the burner gun. The filter set consists of two identical CES designed and fabricated units connected in parallel and containing two 20 mesh screens each. Only one filter is operational at any one time freeing the other for cleaning by either backflushing with water or removal and disassembly. Pressure gauges located upstream and downstream of the filters indicate filter plugging. The pressure difference indicates the degree of plugging in the filter.

The fuel flow rate is measured using a Micromotion mass flow meter (Model C) with digital readout. Flexible lines isolate the meter from any

vibration present in the delivery line.

A steam heat exchanger allows the slurry to be preheated, if so desired, before entering the burner gun. The temperature of the fuel is monitored using a thermocouple and digital display. From the heat exchanger the fuel passes through a section of flexible line to the burner gun. When the gun is removed from the combustion chamber, interrupting fuel flow, this flexible line is connected to a branch of the recirculation line and fuel is kept recirculating through the filters, mass flow meter and heat exchanger, minimizing the possibility of blockage from fuel settling in the lines.

Quick action couplings are located at various points throughout the system to enable flushing of tanks and lines with light oil, water or air.

In order to atomise the fuel either compressed air or steam is used. Compressed air is available from two sources: the University in-house system (capacity 0.4 MPa) or a diesel compressor (capacity 0.8 MPa). The atomisation air flow is measured using a variable area glass tube rotameter, pressure gauge and temperature gauge.

APPENDIX II

Operator's Log Sheets

TEST # 1

5% EXCESS O_2, HFO

AIR ATOMISED

(FT37EMR)

Test No. FT37EMR Name: _____ Date: AUG 8 /84 ①

TIME	fuel press. at pump (psig)	fuel temp. at pump outlet (°F)	fuel press. at burner (psig)	fuel temp. at gun (°F)	fuel temp. at nozzle (°C)	cooling air press. (psig)	cooling air flow (%)	comb. air temp. (°F)	prim. swirl setting	second. swirl setting	burner gun pos'n (in) A- short B- long	stat. medium press. (psig)	air press. at rotameter (psig)	stat. medium flow (% or cfm)	mass flow rate	ΔP combustion air (" wg)	furnace press. (" wg)	oxygen level (%)		ATOM. AIR. TEMP. (°C)	WINDBOX PRESS. ΔP (" wg)	notes
08:00	74	216	58	214	103	x	x	465	5	5	A 14 1/4 B 25 1/4	90	102	28	5.5	2.7	0				2	
08:30	78	216	64	218	105	x	x	425	5	5	A 14 1/4 B 25 1/4	89	103	28	5.5	2	0	3			2	
09:30	75	215	64	215	114	x	x	485	5	5	A 14 1/4 B 25 1/4	89	103	27	5.6	2.3	0	5			2	
10:00	75	215	63	218	114	x	x	480	5	5	A 14 1/4 B 25 1/4	90	100	28	5.5	2.3	0	5			2	
10:30	75	215	64	219	117	x	x	480	5	5	A 14 1/4 B 25 1/4	90	103	27	5.5	2.3	0	5			2	
11:00	75	215	64	219	117	x	x	480	5	5	A 14 1/4 B 25 1/4	90	103	27	5.5	2.3	0	5			2	
11:30	75	215	64	220	103	x	x	475	5	5	A 14 1/4 B 25 1/4	90	103	27	5.5	2.3	0	5			2	
12:00	75	215	64	220	103	x	x	475	5	5	A 14 1/4 B 25 1/4	90	103	27	5.5	2.3	0	5		121	2	
12:30	75	215	64	220	103	x	x	475	5	5	A 14 1/4 B 25 1/4	90	103	27	5.5	2.3	0	5		122	2	
13:00	76	215	64	219	100	x	x	440	5	5	A 14 1/4 B 25 1/4	90	103	27	5.5	2.3	0	5		121	2	
13:30	76	215	64	219	101	x	x	440	5	5	A 14 1/4 B 25 1/4	90	103	27	5.5	2.3	0	5		122	2	
14:00	76	215	64	220	101	x	x	440	5	5	A 14 1/4 B 25 1/4	90	103	27	5.5	2.3	0	5		122	2.1	

Test No. FT37EMR Name: Date: AUG8-9/84 (2)

TIME	fuel press. at pump (psig)	fuel temp. at pump outlet (°F)	fuel press. at burner (psig)	fuel temp. at gun (°F)	fuel temp. at nozzle (°C)	cooling air press. (psig)	cooling air flow (%)	comb. air temp. (°F)	prim. swirl setting	second. swirl setting	burner gun pos'n (in) A- short B- long	stem. medium press. (psig)	air press. at rotameter (psig)	stem. medium flow (% or cfm)	mass flow rate	ΔP combustion air (" wg)	furnace press. (" wg)	oxygen level (%)		ATOM. AIR TEMP (°C)	WINDBOX AIR ΔP (IN WG)	notes
14:30	76	215	64	220	101	x	x	440	5	5	A 14¼ B 25¼	90	103	27	5.5	2.3	0	5		222	2.1	
15:00	76	215	64	220	101	x	x	435	5	5	A 14¼ B 25¼	90	103	27	5.5	2.3	0	5		224	2.1	
15:30	76	215	64	220	101	x	x	435	5	5	A 14¼ B 25¼	90	103	27	5.5	2.3	0	5		224	2.1	
16:00	76	215	64	219	101	x	x	440	5	5	A 14¼ B 25¼	90	103	27	5.5	2.3	0	5		224	2.1	
											A											
AUG 9/84											B											
08:30	75	215	63	220	101	x	x	485	5	5	A 14¼ B 25¼	90	103	27	5.5	2.4	0	5		115	2.1	
09:30	75	215	63	220	101	x	x		5	5	A 14¼ B 25¼	90	103	27	5.5	2.4	0	5		120	2.1	
10:00	75	215	63	219	101	x	x		5	5	A 14¼ B 25¼	90	103	27	5.5	2.4	0	5		120	2.1	
											A											
											B											
											A											
											B											
											A											
											B											
											A											
											B											

TEST # 2

5% EXCESS O_2, HFO

STEAM ATOMISED

(FF3EMR)

Test No. FT38EMR Name: _____ Date: AUG9-10 '84 (1)

TIME	fuel press. at pump (psig)	fuel temp. at pump outlet (°F)	fuel press. at burner (psig)	fuel temp. at gun (°F)	fuel temp. at nozzle (°C)	cooling air press. (psig)	cooling air flow (%)	comb. air temp. (°F)	prim. swirl setting	second. swirl setting	burner gun pos'n (in) A- short B- long	atom. medium press. (psig)	air press. at rotameter (psig)	atom. medium flow (% or cfm)	mass flow rate	Δp combustion air (" wg)	furnace press. (" wg)	oxygen level (%)		ATOM. STEAM TEMP. (°C)	WINDBOX PRESS Δp (IN WG)	notes
11:15	75	215	54	219	101	x	x	475	5	5	A 14¼ / B 25¼	90	x	x	5.5	2.4	0	5			2.1	
12:00	77	215	56	220	115	x	x	485	5	5	A 14¼ / B 25¼	90	x	x	5.5	2.4	0	5			2.1	
12:30	77	215	54	220	116	x	x	480	5	5	A 14¼ / B 25¼	90	x	x	5.5	2.4	0	5			2.1	
13:00	77	215	54	220	110	x	x	300	5	5	A 14¼ / B 25¼	90	x	x	5.5	2.4	0	5			2.1	
14:15	77	215	55	220	x	x	x	490	5	5	A 14¼ / B 25¼	90	x	x	5.5	2.4	0	5		115	2.1	CHANGED FUEL TEMP AT NOZZLE TO STEAM TEMP
15:00	77	215	55	220	x	x	x	490	5	5	A 14¼ / B 25¼	90	x	x	5.5	2.4	0	5		122	2.1	
15:30	77	215	55	219	x	x	x	495	5	5	A 14¼ / B 25¼	90	x	x	5.5	2.4	0	5		123	2.1	
16:00	77	215	56	222	x	x	x	495	5	5	A 14¼ / B 25¼	90	x	x	5.5	2.4	0	5		121	2.1	
											A / B											
AUG 10																						
08:00	72	220	56	220	x	x	x	505	5	5	A 14¼ / B 25¼	90	x	x	5.5	2.6	0	5		118	2.7	
08:30	77	219	55	220	x	x	x	505	5	5	A 14¼ / B 25¼	90	x	x	5.5	2.6	0	5		113	2.7	
09:00	77	219	56	219	x	x	x	505	5	5	A 14¼ / B 25¼	90	x	x	5.5	2.5	0	5		113	2.7	

Test No. FT 38 EMR Name: _____ Date: AUG 10 /84 (2)

TIME	fuel press. at pump (psig)	fuel temp. at pump outlet (°F)	fuel press. at burner (psig)	fuel temp. at gun (°F)	fuel temp. at nozzle (°C)	cooling air press. (psig)	cooling air flow (%)	comb. air temp. (°F)	prim. swirl setting	second. swirl setting	burner gun pos'n (in) A- short B- long	atom. medium press. (psig)	air press. at rotameter (psig)	atom. medium flow (% or cfm)	mass flow rate	ΔP combustion air (" wg)	furnace press. (" wg)	oxygen level (%)		ATOM. STEAM TEMP. (°C)	WINDBOX PRESS ΔP (IN WG)	notes
09:30	77	219	56	218	x	x	x	500	5	5	A 14¼ B 25¼	90	x	x	5.5	2.5	0	5		115	2.7	
10:00	75	219	57	217	x	x	x	500	5	5	A 14¼ B 25¼	90	x	x	5.5	2.5	0	5		113	2.7	
10:30	75	219	55	220	x	x	x	500	5	5	A 14¼ B 25¼	90	x	x	5.5	2.5	0	5		115	2.7	
11:00	75	219	55	219	x	x	x	500	5	5	A 14¼ B 25¼	90	x	x	5.5	2.5	0	5		115	2.7	
11:30	76	215	55	219	x	x	x	500	5	5	A 14¼ B 25¼	90	x	x	5.5	2.5	0	5		113	2.7	
12:00	77	213	54	220	x	x	x	495	5	5	A 14¼ B 25¼	90	x	x	5.5	2.5	0	5		118	2.7	
12:30	76	215	55	219	x	x	x	495	5	5	A 14¼ B 25¼	90	x	x	5.5	2.5	0	5		116	2.7	
13:00	77	215	55	219	x	x	x	495	5	5	A 14¼ B 25¼	90	x	x	5.5	2.5	0	5		115	2.7	
											A B											
											A B											
											A B											
											A B											

TEST # 3

3% EXCESS O_2, CM

AIR ATOMISED

(FF34E1R)

Test No. FT34 EMR Name: Date: JULY 11 /84 ①

TIME	fuel press. at pump (psig)	fuel temp. at pump outlet (°F)	fuel press. at burner (psig)	fuel temp. at gun (°F)	fuel temp. at nozzle (°C)	cooling air press. (psig)	cooling air flow (%)	comb. air temp. (°F)	prim. swirl setting	second. swirl setting	burner gun pos'n (in) A- short B- long	atom. medium press. (psig)	air press. at rotameter (psig)	atom. medium flow (% or cfm)	mass flow rate (lb/min)	Δp combustion air ("wg)	furnace press. ("wg)	oxygen level (%)	WINDBOX PRESSURE Δp (in. w.g.)	air Temp @ Rotameter (°F)	PUMP SPEED SETTING	notes
07:30	92	90	67	84	32	0	0	549	4	4	A 9½ B 24	96	100	36	9.7	1.4	0	3	1.9	106	6	
08:00	92	79	66	79	29	0	0	550	4	4	A 9½ B 24	95	100	36	9.6	1.5	0	3	1.8	107	6	
08:30	92	90	65	87	34	0	0	550	4	4	A 9½ B 24	95	100	36	9.6	1.4	0	2	1.7	111	6	
09:00	90	98	66	94	38	0	0	550	4	4	A 9½ B 24	95	100	36	9.6	1.3	0	3	1.9	111	6	
10:30	86	102	66	94	39	0	0	550	4	4	A 9½ B 24	95	100	36	9.7	1.3	0	3	1.8	112	6	
11:30	86	102	70	99	41	0	0	550	4	4	A 9½ B 24	95	100	36	9.7	1.5	0	2	1.8	112	6	
13:15	78	110	63	105	39	0	0	550	4	4	A 9½ B 24	95	101	36	9.7	1.4	0	5	1.7	118	2	
15:15	74	111	68	109	38	0	0	525	4	4	A 9½ B 24	95	100	35	9.7	1.7	-0.05	3	2.1	118	2	
16:23	86	110	71	104	38	0	0	525	4	4	A 9½ B 24	96	101	34	9.7	1.8	0	3	2.2	113	2	
16:50	85	110	68	105	37	0	0	525	4	4	A 9½ B 24	96	100	35	9.6	1.9	-0.15	5	2.1	108	2	
17:20	85	110	70	104	38	0	0	525	4	4	A 9½ B 24	96	100	34	9.5	1.8	0	3.5	2.0	108	2	
											A B											

Test No. FT34 EMR Name: Date: JULY 12/84. (2)

TIME	fuel press. at pump (psig)	fuel temp. at pump outlet (°F)	fuel press. at burner (psig)	fuel temp. at gun (°F)	fuel temp. at nozzle (°C)	cooling air press. (psig)	cooling air flow (S)	comb. air temp. (°F)	prim. swirl setting	second. swirl setting	burner gun pos'n (IN) A- short B- long	atom. medium press. (psig)	air press. at rotameter (psig)	atom. medium flow (S or cfm)	mass flow rate (lb/min.)	Δp combustion air (" wg)	furnace press. (" wg)	oxygen level (%)	windbox PRESSURE Δp (in. W.G.)	AIR TEMP. AT ROTAMETER (°F)	PUMP SPEED SETTING	notes
08:20	102	83	72	80	30	0	0	515	4	4	A 9½ B 24	95	100	35	9.7	1.8	0		2.5	114	2	
09:00	98	85	70	84	31	0	0	515	4	4	A 9½ B 24	95	101	35	9.7	1.8	0	3	2.4	109	2	
11:00	88	92	62	90	32	0	0	515	4	4	A 9¼ B 23⅞	94	100	36	9.7	1.9	+.05	3	2.4	112	2	
11:30	89	93	62	90	31	0	0	515	4	4	A 9¼ B 23⅞	94	100	36	9.7	1.9	0	3	2.4	111	2	
12:00	88	93	59	91	31	0	0	515	4	4	A 9¼ B 23⅞	94	100	36	9.6	1.9	0	3	2.4	111	2	
12:30	100	80	63	78	26	0	0	515	4	4	A 9¼ B 23⅞	94	100	36	9.3	1.7	0	6	2.4	111	2	
13:00	100	80	65	78	26	0	0	515	4	4	A 9¼ B 23⅞	94	100	36	9.5	1.9	0	3	2.4	112	2	
13:30	98	80	64	78	27	0	0	515	4	4	A 9¼ B 23⅞	94	100	36	9.5	1.9	0	2.5	2.4	113	2	
14:00	100	84	64	82	28	0	0	515	4	4	A 9¼ B 23⅞	94	100	36	9.7	1.9	0	3	2.4	116	2	
14:30	100	86	63	84	29	0	0	510	4	4	A 9¼ B 23⅞	94	100	36	9.7	1.9	0	3	2.4	117	2	
15:00	101	90	62	77	30	0	0	510	4	4	A 9¼ B 23⅞	94	100	36	9.7	1.9	0	3	2.4	117	2	
15:30	99	92	63	89	30	0	0	510	4	4	A 9¼ B 23⅞	94	100	36	9.7	1.9	0	3	2.5	117	2	

Test No. FT 34 EMR Name: Date: JULY 13/84 (3)

TIME	fuel press. at pump (psig)	fuel temp. at pump outlet (°F)	fuel press. at burner (psig)	fuel temp. at gun (°F)	fuel temp. at nozzle (°C)	cooling air press. (psig)	cooling air flow (%)	comb. air temp. (°F)	prim. swirl setting	second. swirl setting	burner gun pos'n (A) A- short B- long	atom. medium press. (psig)	air press. at rotameter (psig)	atom. medium flow (% or cfm)	mass flow rate (lb/min)	Δp combustion air (" wg)	furnace press. (" wg)	oxygen level (%)	WINDBOX PRESSURE Δp (in. w.c.)	AIR TEMP. AT ROTAMETER (°F)	PUMP SPEED SETTING	notes
16:00	98	94	68	92	31	0	0	510	4	4	A 9 1/4 B 23 7/8	95	100		9.7	1.9	0	3	2.8	120	2	
16:30	98	94	62	92	32	0	0	510	4	4	A 9 1/4 B 23 7/8	95	100		9.8	1.9	0	3	2.8	119	2	
17:00	98	95	62	92	32	0	0	515	4	4	A 9 1/4 B 23 7/8	95	100		9.9	1.9	0	3	2.8	118	2	
17:30	95	95	61	92	32	0	0	515	4	4	A 9 1/4 B 23 7/8	95	100		9.4	1.9	0	3	2.7	118	2	
18:00	95	95	61	90	32	0	0	510	4	4	A 9 1/4 B 23 7/8	95	100		9.9	1.9	0	3	2.8	118	2	
18:30	92	93	57	90	31	0	0	515	4	4	A 9 1/4 B 23 7/8	94	100	36	9.6	2.0	0	3.5	2.5	116	2	
19:18	104	88	60	82	27	0	0	295	4	4	A 9 1/4 B 23 7/8	94	100	36	9.7	2.0	+0.1	5.5	2.0	116	2	
											A B											
											A B											
											A B											
											A B											
											A B											

Test No. FT3HEMR Name: Date: JULY 13/84 ④

TIME	fuel press. at pump (psig)	fuel temp. at pump outlet (°F)	fuel press. at burner (psig)	fuel temp. at gun (°F)	fuel temp. at nozzle (°C)	cooling air press. (psig)	cooling air flow (%)	comb. air temp. (°F)	prim. swirl setting	second. swirl setting	burner gun pos'n (in) A- short B- long	steam. medium press. (psig)	air press. at rotameter (psig)	steam. medium flow (% or cfm)	mass flow rate (lb/min)	ΔP combustion air (" wg)	furnace press. (" wg)	oxygen level (%)	WINDBOX PRESSURE ΔP (in. W.G.)	AIR TEMPERATURE AT ROTAMETER (°F)	PUMP SPEED SETTING	notes
08:15	91	84	64	82	28	0	0	525	4	4	A 9 3/8 B 23 7/8	96	101	36	9.7	2.2	+0.1	3	2.6	116	2	
09:10	89	88	61	84	29	0	0	515	4	4	A 9 3/8 B 23 7/8	96	101	36	9.7	1.9	0	3	2.6	119	1 3/4	
09:30	89	90	61	89	30	0	0	515	4	4	A 9 3/8 B 23 7/8	96	101	36	9.7	1.8	-.4	4	2.6	119	1 3/4	
10:00	89	82	62	90	30	0	0	515	4	4	A 9 3/8 B 23 7/8	96	101	36	9.6	1.8	0	4	2.6	121	1 3/4	
10:30	76	83	58	91	31	0	0	520	4	4	A 9 3/8 B 23 7/8	96	101	36	9.6	1.8	-.5	4	2.6	122	2	
11:00	76	93	58	92	31	0	0	520	4	4	A 9 3/8 B 23 7/8	96	101	36	9.6	1.8	-.5	4	2.6	123	2	
12:00	80	94	63	93	32	0	0	520	4	4	A 9 3/8 B 23 7/8	96	101	36	9.7	1.8	0	3	2.6	123	2	
12:30	76	85	55	94	32	0	0	475	4	4	A 9 3/8 B 23 7/8	96	101	36	9.7	2.7	0	5	2.9	123	2	BEGIN FT3SEMR 5% EXCESS O_2
13:30	90	82	63	80	27	0	0	475	4	4	A 9 3/8 B 23 7/8	96	101	36	9.7	2.7	0	5	2.9	123	2	
14:00	89	81	61	80	26	0	0	475	4	4	A 9 3/8 B 23 7/8	96	101	36	9.7	2.7	0	5	2.9	123	2	
14:30	87	84	62	83	28	0	0	475	4	4	A 9 3/8 B 23 7/8	96	100	36	9.7	2.6	0	5	3.5	123	2	
16:36	82	94	62	92	32	0	0	475	4	4	A 9 3/8 B 23 7/8	95	101	36	9.7	2.7	0	5	3.4	124	2	

TEST # 4

5% EXCESS O_2, CW

AIR ATOMISED

(FT35E4R)

Test No. FT35EMR Name: _____ Date: JULY 16/84. (1)

TIME	fuel press. at pump (psig)	fuel temp. at pump outlet (°F)	fuel press. at burner (psig)	fuel temp. at gun (°F)	fuel temp. at nozzle (°C)	cooling air press. (psig)	cooling air flow (%)	comb. air temp. (°F)	prim. swirl setting	second. swirl setting	burner gun pos'n (IN) A- short B- long	atom. medium press. (psig)	air press. at rotameter (psig)	atom. medium flow (% or cfm)	mass flow rate (lb/min)	Δp combustion air ("wg)	furnace press. ("wg)	oxygen level (%)	windbox Δp ("w.c.)	AIR TEMPERATURE AT ROTAMETER (°F)	PUMP SPEED SETTING	notes
08:45	82	88	61	85	-	0	0	485	4	4	A 9 3/8 B 23 3/4	93	99	36	9.7	2.8	+0.07	5	3.8	116	2	
09:15	80	90	61	88	-	0	0	490	4	4	A 9 3/8 B 23 3/4	94	101	36	9.7	2.8	+0.07	5	3.8	119	2	
10:00	78	93	59	90	-	0	0	470	4	4	A 9 3/8 B 23 3/4	94	101	36	9.6	2.8	0	5	3.8	118	2	
10:30	79	93	59	92	32	0	0	470	4	4	A 9 3/8 B 23 3/4	94	100	36	9.7	2.8	0	5	3.8	117	2	
11:00	80	96	59	92	32	0	0	470	4	4	A 9 3/8 B 23 3/4	94	100	36	9.7	2.8	0	5	3.8	117	2	
11:30	77	96	61	94	33	0	0		4	4	A 9 3/8 B 23 3/4	94	100	36	9.7	2.8	0	5	3.8	117	2	
12:00	77	96	61	94	33	0	0	470	4	4	A 9 3/8 B 23 3/4	94	100	36	9.7	2.8	0	5	3.8	117	2	
13:30	79	99	59	96	34	0	0	485	4	4	A 9 3/8 B 23 3/4	94	101	36	9.7	2.8	0	5	3.8	117	2	
14:30	82	84	61	83	29	0	0	475	4	4	A 9 3/8 B 23 3/4	94	101	36	9.7	2.8	0	5	3.8	117	2	
15:00	80	84	61	83	28	0	0	475	4	4	A 9 3/8 B 23 3/4	94	101	36	9.7	2.8	0	6	3.8	121	2	
15:30	80	86	60	86	29	0	0	475	4	4	A 9 3/8 B 23 3/4	94	100	36	9.7	2.8	0	5	3.8	121	2	
16:00	DOWN										A B											NOZZLE PLUGGED - FOREIGN MATERIAL IN FUEL

Test No. FT35EMR Name: Date: JULY 17/84. (2)

TIME	fuel press. at pump (psig)	fuel temp. at pump outlet (°F)	fuel press. at burner (psig)	fuel temp. at gun (°F)	fuel temp. at nozzle (°C)	cooling air press. (psig)	cooling air flow (S)	comb. air temp. (°F)	prim. swirl setting	second. swirl setting	burner gun pos'n (W) A- short B- long	atom. medium press. (psig)	air press. at rotameter (psig)	atom. medium flow (S or c/m)	mass flow rate (lb/min)	Δp combustion air ("wg)	furnace press. ("wg)	oxygen level (%)	WINDBOX PRESSURE Δp (in. W.C.)	AIR TEMP. AT ROTAMETER	PUMP SPEED SETTING	notes
08:45	80	94	64	92	32	0	0	510	4	4	A 9 3/8 B 24	95	100	36	9.7	2.0	0	5	2.8	115	2	
09:45	80	94	65	92	32	0	0	480	4	4	A 9 3/8 B 23 3/8	95	100	36	9.7	2.6 (2.8)*	0	5.5	2.8	115	2	*10:00 COMBUSTION AIR • 2.8
10:30	86	81	68	80	27	0	0	470	4	4	A 9 3/8 B 23 3/8	95	100	36	9.7	2.7	0	6.5	3.7	119	2	
10:45	90	80	66	79	27	0	0	470	4	4	A 9 3/8 B 23 3/8	95	100	36	9.7	2.7	0	5	3.7	119	2	FIRE MORE STABLE AT LOWER FUEL TEMPERATURE
11:00	90	80	66	79	27	0	0	470	4	4	A 9 3/8 B 23 3/8	95	100	36	9.7	2.7	0	5	3.7	119	2	
11:30	85	85	63	83	28	0	0	470	4	4	A 9 3/8 B 23 3/8	95	100	36	9.7	2.7	0	5	3.7	119	2	
12:00	81	78	61	86	30	0	0	470	4	4	A 9 3/8 B 23 3/8	95	100	36	9.7	2.7	0	5	3.7	119	2	
12:30	80	91	59	89	*	0	0	470	4	4	A 9 3/8 B 23 3/8	95	100	36	9.6	2.7	0	5	3.7	121	2	
13:00	100	89	74	89	*	0	0	470	4	4	A 9 3/8 B 23 3/8	95	100	36	9.7	2.7	0	8	3.7	121	2	
13:30	88	96	66	93	*	0	0	470	4	4	A 9 3/8 B 23 3/8	95	100	36	9.5	2.7	0	7	3.7	122	2	
14:00	80	96	61	94	*	0	0	470	4	4	A 9 3/8 B 23 3/8	95	100	36	9.7	2.7	0	6.5	3.6	123	2	
14:30	80	96	62	94	*	0	0	470	4	4	A 9 3/8 B 23 3/8	95	100	36	9.7	2.7	0	8	3.6	123	2	

Test No. FT 35 EMR Name: Date: JULY 13/84 (3)

TIME	fuel press. at pump (psig)	fuel temp. at pump outlet (°F)	fuel press. at burner (psig)	fuel temp. at gun (°F)	fuel temp. at nozzle (°C)	cooling air press. (psig)	cooling air flow (%)	comb. air temp. (°F)	prim. swirl setting	second. swirl setting	burner gun pos'n (W) A- short B- long	atom. medium press. (psig)	air press. at rotameter (psig)	atom. medium flow (% or cfm)	mass flow rate (lb/min)	Δp combustion air (" wg)	furnace press. (" wg)	oxygen level (%)	WINDBOX PRESSURE Δp (in. w.c.)	AIR TEMP. AT ROTAMETER (°F)	PUMP SPEED SETTING	notes
15:00	80	94	64	92	x	0	0	475	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	2.7	-4	8	3.6	123	2	
15:30	77	94	61	94	x	0	0	475	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	2.7	0	7	3.6	124	2	
16:38	105	93	72	92	x	0	0	475	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	2.7	0	8.4	3.5	124	2	SOOT PROBING
17:10	106	93	70	92	x	0	0	475	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	2.7	0	11	3.5	120	2	"
17:30	107	95	71	93	x	0	0	475	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	2.7	0	-	3.5	120	2	CLEAN GAS SAMPLING FILTER
18:00	110	98	71	96	x	0	0	475	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	2.7	0	5	3.5	120	2	SHUTDOWN
											A B											
											A B											
											A B											
											A B											
											A B											
											A B											

Test No. FT35EMR

Date: JULY 18/84

TIME	PRIMETER fuel press. at pump (psig)	fuel temp. at pump outlet (°F)	fuel press. at burner (psig)	fuel temp. at gun (°F)	fuel temp. at nozzle (°C)	cooling air press. (psig)	cooling air flow (%)	comb. air temp. (°F)	prim. swirl setting	second. swirl setting	burner gun pos'n (in) A- short B- long	steam: medium press. (psig)	air press. at rotameter (psig)	steam: medium flow (% or cfm)	mass flow rate (lb/min)	ΔP combustion air (" wg)	furnace press. (" wg)	oxygen level (%)	WINDBOX PRESSURE ΔP (in. W.C.)	AIR TEMPERATURE AT ROTAMETER (°F)	PUMP SPEED SETTING	notes
08:20	81	96	62	93	33	0	0	500	4	4	A 9 3/8 B 23 3/8	94	100	36	9.7	1.7	0	3	2.2	111	2	WARMING UP THROAT 782°C
10:00	102	90	60	81	27	0	0	480	4	4	A 9 3/8 B 23 3/8	94	101	36	9.7	2.6	0	7	2.2	113	-	PUMPING FROM TANKER 09:45
10:30	105	88	65	82	28	0	0	480	4	4	A 9 3/8 B 23 3/8	94	100	36	9.7	2.6	0	7	3.4	119	-	FUEL TOO HOT
11:15	105	87	66	82	28	0	0	480	4	4	A 9 3/8 B 23 3/8	94	100	36	9.7	2.6	0	7	3.4	120	-	
12:00	109	87	67	82	28	0	0	475	4	4	A 9 3/8 B 23 3/8	95	100	36	9.7	2.6	0	5	3.4	122	-	COMPRESSOR FAILURE
17:07	100	88	69	84	29	0	0	485	4	4	A 9 3/8 B 23 3/8	95	100	36	9.7	2.7	0	5	-	122	-	BACK AGAIN BY 14:30
											A B											
											A B											
											A B											
											A B											
											A B											
											A B											

Test No. FT35 EMR Name: Date: JULY 19 1984 (5)

TIME	fuel press. at pump (psig)	fuel temp. at pump outlet (°F)	fuel press. at burner (psig)	fuel temp. at gun (°F)	fuel temp. at nozzle (°C)	cooling air press. (psig)	cooling air flow (%)	comb. air temp. (°F)	prim. swirl setting	second. swirl setting	burner gun pos'n (in) A- short B- long	atom. medium press. (psig)	air press. at rotameter (psig)	atom. medium flow (% or cfm)	mass flow rate (lb/min)	Δp combustion air (" wg)	furnace press. (" wg)	oxygen level (%)	VINDOR PRESSURE Δp (in. W.C.)	AIR TEMP. AT ROTAMETER (°F)	PUMP SPEED SETTING	notes
09:30	96	87	69	92	x	0	0	515	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	1.7	0	4	2.3	116	x	
10:00	92	86	69	92	x	0	0	515	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	1.7	0	3	2.3	118	x	
10:30	95	86	68	92	x	0	0	525	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	1.7	0	3	2.3	119	x	
11:00	95	86	67	92	x	0	0	520	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	1.7	0	4	2.3	119	x	
11:30	95	87	66	82	x	0	0	520	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	1.7	0	3	2.3	120	x	
12:00	92	86	67	82	x	0	0	520	4	4	A 9 3/8 B 23 7/8	95	100	36	9.5	1.7	0	3	2.3	121	x	
12:36	99	88	67	86	x	0	0	525	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	1.7	+.03	4.6	2.3	122	2	12:35 BACK TO DAY TANK · PROBING
13:00	102	88	67	85	x	0	0	525	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	1.7	+.03	6	2.3	121	2	
13:30	104	88	68	86	x	0	0	525	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	1.7	+.03	5	2.3	121	2	
14:00	105	92	68	91	32	0	0	525	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	1.7	+.02	5	2.3	120	2	
14:30	105	96	67	93	33	0	0	525	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	1.7	+.02	4	2.3	121	2	
15:00	97	96	65	95	34	0	0	520	4	4	A 9 3/8 B 23 7/8	95	100	36	9.7	1.7	+.02	4	2.3	121	2	

TEST # 5

5% EXCESS O_2, CM

STEAM ATOMISED

(FT36EMR)

Test No. FT 36 EMR Name: Date: JULY 19/84. (1)

TIME	PARAMETER: fuel press. at pump (psig)	fuel temp. at pump outlet (°F)	fuel press. at burner (psig)	fuel temp. at gun (°F)	fuel temp. at nozzle (°C)	cooling air press. (psig)	cooling air flow (S)	comb. air temp. (°F)	prim. swirl setting	second. swirl setting	burner gun pos'n (IN) A- short B- long	atom. medium press. (psig) STEAM	air press. at rotameter (psig)	atom. medium flow (S or cfm)	mass flow rate (lb/min.)	ΔP combustion air (" wg)	furnace press. (" wg)	oxygen level (%)	WINDBOX PRESSURE ΔP (in. W.C.)	STEAM TEMP	PUMP SPEED SETTING	notes
16:00	77	97	47	96	-	0	0	500	4	4	A 9 3/8 B 23 1/8	96	-	-	9.5	2.1	0	3	2.9	127	-	STEAM ATOMIZED QUALITY 1.56%
17:00	90	89	46	89	42	0	0	490	4	4	A 9 3/8 B 23 1/8	84	-	-	9.7	2.5	0	5	2.9	127	-	
17:53	81	98	44	96	47	0	0	500	4	4	A 9 3/8 B 23 1/8	83	-	-	9.7	2.5	0	5	3.1	-	2	
18:25	80	99	44	96	49	0	0	485	4	4	A 9 3/8 B 23 1/8	86	-	-	9.6	2.1	0	6	3.1	-	2	
19:00	79	98	50	81	40	0	0	485	4	4	A 9 3/8 B 23 1/8	86	-	-	9.7	2.7	0	6	3.1	-	-	SWITCH OVER TO SMALL MOYNO PUMP
20:00	79	89	49	82	38	0	0	485	4	4	A 9 3/8 B 23 1/8	87	-	-	9.6	2.6	-0.1	5.5	2.9	-	-	
20:45	76	87	48	80	39	0	0	300	4	4	A 9 3/8 B 23 1/8	86	-	-	9.5	2.7	0	6.5	2.4	-	-	
21:33	75	86	46	80	40	0	0	525	4	4	A 9 3/8 B 23 1/8		-	-	9.7	2.7	0	5	3.3	-	-	
22:00	74	86	48	80	39	0	0	520	4	4	A 9 3/8 B 23 1/8	86	-	-	9.7	2.7	0	5	3.3	-	-	
22:30	70	86	48	80	39	0	0	520	4	4	A 9 3/8 B 23 1/8	86	-	-	9.7	2.7	0	5	3.3	-	-	STEAM 100PSI/340F
23:00	69	85	48	80	39	0	0	520	4	4	A 9 3/8 B 23 1/8	86	-	-	9.7	2.7	0	5	3.3	-	-	
23:45	65	86	43	87	41	0	0	515	4	4	A 9 3/8 B 23 1/8	86	-	-	9.7	2.7	0	5	3.3	-	-	BACK ON DAY TANK

Test No. FT36EMR Name: Date: JULY19/84 - JULY20/84 (2)

TIME	fuel press. at pump (psig)	fuel temp. at pump outlet (°F)	fuel press. at burner (psig)	fuel temp. at gun (°F)	fuel temp. at nozzle (°C)	cooling air press. (psig)	cooling air flow (%)	comb. air temp. (°F)	prim. swirl setting	second. swirl setting	burner gun pos'n (in) A- short B- long	atom. medium press. (psig)	air press. at rotameter (psig)	atom. medium flow (% or cfm)	mass flow rate (lb/min)	Δp combustion air (" wg)	furnace press. (" wg)	oxygen level (%)	WINDBOX PRESSURE Δp (in. w.c.)		PUMP SPEED SETTINGS	notes
JULY 20/84 00:00	70	84	43	87	40	0	0	505	4	4	A 9 3/8 B 23 7/8	86	-	-	9.7	2.7	0	5	3.3			
00:30	70	84	44	82	41	0	0	515	4	4	A 9 3/8 B 23 7/8	86	-	-	9.7	2.7	0	5	3.3			
01:00	66	86	43	82	39	0	0	500	4	4	A 9 3/8 B 23 7/8	86	-	-	9.7	2.7	0	5	3.3			
01:30	65	89	42	85	40	0	0	500	4	4	A 9 3/8 B 23 7/8	86	-	-	9.8	2.7	0	5	3.3			
02:00	64	90	43	86	41	0	0	500	4	4	A 9 3/8 B 23 7/8	86	-	-	9.7	2.7	0	5	3.3		1	
02:30	60	92	42	89	41	0	0	475	4	4	A 9 3/8 B 23 7/8	86	-	-	9.7	2.7	0	-	3.3		1	5% BUT O2 METER TURNED OFF
03:00	60	94	41	90	42	0	0	455	4	4	A 9 3/8 B 23 7/8	86	-	-	9.6	2.7	0	-	3.3		1	5% O2 - AIR PRE-HEATER KEEPS GOING OUT
											A B											NO CHANGE IN STEAM QUALITY STILL 1.36%
											A B											
											A B											
											A B											
											A B											

APPENDIX III

Calculation Procedures

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Figure 1: Dry flue gas volumeric combustion chart iii

1. General

Routine calculations performed during each test are described. Such calculations enable the determination of the various parameters required to establish desired test conditions.

2. Thermal input

Based on the calorific value of the fuel, the fuel flow rate for a desired thermal input is determined from the following equation:

$$Q = \dot{m}\Delta H_c \qquad (1)$$

where: Q = thermal input/[MW]

$\dot{m}$ = fuel mass flow rate/[kg s^{-1}]

ΔH_c = net corrected calorific value/[MJ kg^{-1}]

A micromotion mass flow meter is used to monitor the fuel flow rate and thereby maintain a constant thermal input.

3. Combustion air flow rate

Based on an ultimate analysis of the fuel, stoichiometric combustion calculations enable the determination of the amount of combustion air required for complete combustion. Using these calculations the volumetric air flow rate necessary to generate various excess oxygen levels in the flue gas can be determined. The required flow rate of combustion air is also calculated and is measured using an orifice plate mounted in the air duct and a differential U-type monometer. Flow rate is controlled by means of a remote controlled damper.

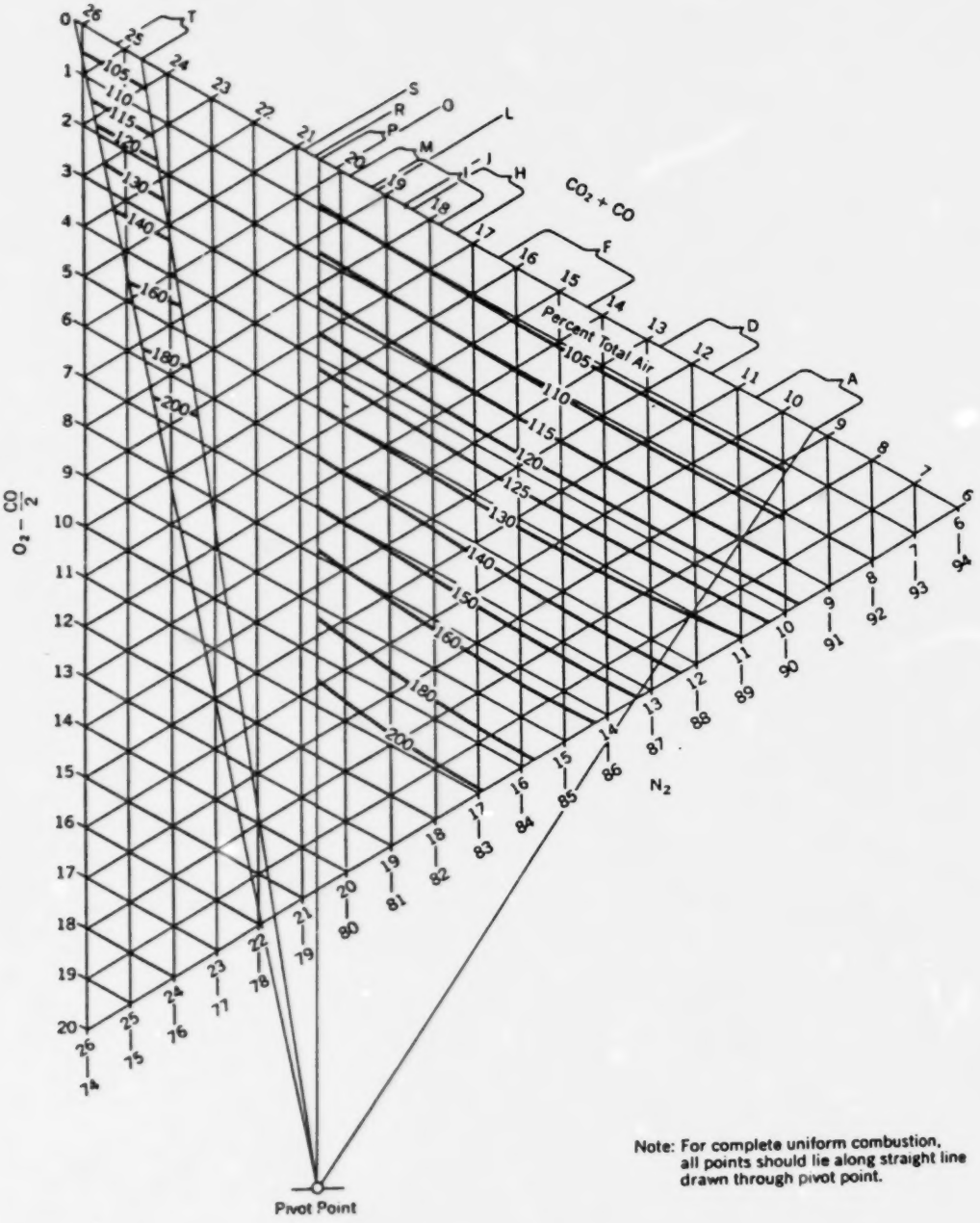

Fig. 1: Dry flue gas volumetric combustion chart

Excess oxygen levels in the flue gas are monitored using gas analysis equipment. The readings obtained can be plotted on a dry flue gas volumetric combustion chart shown in Fig. 1 and checked with the plot of stoichiometric conditions.

4. Atomization and cooling air flowrates

The atomization and cooling air flowrates are measured using variable-area rotameters.

The following equation is used to determine the maximum scfm value for the rotameters at various operating conditions:

$$\text{AIR SCFM MAX (at 100\% Reading)} = \frac{45.3}{\left[\frac{(SG_F)(14.7)(T_{op})}{(SG_W)(530)(P_{op})}\right]^{1/2}}$$

where: 45.3 = rotameter max. flow rate at STP [scfm]

SG_F = specific gravity of fluid/[-]

T_{op} = temperature of air/[°R]

SG_W = specific gravity of water/[-]

P_{op} = pressure of air/[psia]

5. Furnace load

The flowrate and inlet and outlet temperatures of the combustion chamber cooling water enable the determination of furnace load. It is calculated using the equation:

$$Q = \dot{m} c_p \Delta T \qquad (2)$$

where: Q = furnace load/[kW]

$\dot{m}$ = mass flow rate of cooling water/[kg s^{-1}]

C_p = specific heat of water/[kJ kg^{-1} K^{-1}]

ΔT = temperature rise of cooling water/[K]

Cooling water temperatures are automatically logged at 2 minute intervals and the flowrate is held constant for the duration of a test. When water temperatures reach a steady state condition, an average is taken and ΔT is determined. The furnace load calculated represents the heat being removed from the furnace by the combustion chamber walls.

APPENDIX IV:

Characterization of Fuel, Ash, and Particulate Emmissions

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Figure 2: Model 240 Elemental Analyzer Program ix

Figure 3: Combustion Train x

1. General

This appendix briefly describes the various analytical tests used to characterize fuels, ash and particulate emissions. The analyses are performed in the Coal Research Laboratory at the Technical University of Nova Scotia (TUNS).

In general, ASTM or ISO test methods are used. In some cases, when the samples are small (less than 1.0g) alternative thermogravimetric analyses are used.

2. Moisture content

Moisture is determined by measuring the weight loss of the sample when heated under rigidly controlled conditions of temperature, time and atmosphere, sample weight and equipment specifications. Wherever sample conditions are suitable ASTM procedure D3173-73 or ISO is followed.

2.1 Apparatus

(a) TGA - STONE model 7050 TGA analyzer.

(b) Drying oven - The oven is so constructed as to have a uniform temperature in all parts, a minimum of air space, and be capable of temperature regulation between 104° and 110°C. Provision is made for renewing the preheated air in the oven at the rate of two to four times a minute.

(c) Capsules - A convenient form is a porcelain capsule, 22 mm in depth and 44 mm in diameter, or a fused silica capsule of similar shape. This is used with a well-fitting flat cover.

2.2 Procedure

(1) For samples weighing less than one gram it is necessary to resort to thermogravimetric analysis for evaluating the moisture content of the sample. The sample (a minimum of 20 mg) is placed in the sample holder exposed to air as the surrounding gas and the temperature is raised at the rate of 20° C/min until it reaches 100°C, where it is held for one hour. The moisture content is then evaluated from the weight loss incurred under these conditions.

(2) For samples weighing one gram or more, it is feasible to use the drying oven in the manner prescribed by the ASTM or ISO procedures. Heat the empty capsules under the conditions at which the sample is to be dried, place the stopper or cover on the capsule, cool over a desiccant for 15 to 30 minutes and weigh. Quickly transfer one gram of the sample into the capsule, close, and weigh at once. After removing the covers, quickly place the capsules in a preheated oven at (104°C to 110°C) through which passes a current of air dried by H_2SO_4 (sp.gr.1.84) or other suitable desiccant. Close the oven at once and heat for one hour. Open the oven, cover the capsules quickly, and cool in a desiccator over desiccant. Weigh as soon as cold.

3. Volatile matter

Volatile matter is determined by measuring the loss in weight resulting from heating the sample under rigidly controlled conditions. The measured weight loss, corrected for moisture, establishes the volatile matter content. Wherever sample conditions are suitable, ASTM procedure D3175-73 or ISO is followed.

3.1 Apparatus

(a) TGA - STONE model 7050 TGA analyzer.

(b) Crucible - Platinum crucible 15 ml capacity.

(c) Furnace - electrically heated vertical muffle furnace regulated to maintain a temperature of 950° ± 7°C in the crucible as measured by a thermocouple positioned in the furnace.

3.2 Procedure

(1) For samples weighing less than one gram it is necessary to resort to thermogravimetric analysis for evaluating the moisture content of the sample. The sample (a minimum of 20 mg) is placed in the sample holder exposed to air as the surrounding gas and the temperature is raised at the rate of 20°C/min until it reaches 100°C where it is held for one hour to expel moisture. The temperature is then raised upto 800°C at the rate of 20°C/min and the volatiles determined from the weight loss incurred after correction for moisture content.

(2) For samples weighing one gram or more, it is possible to use ASTM or ISO procesures. Weigh one gram of the sample in a preweighed platinum cruicible, close with the cover and place on platinum or nichrome wire supports in a furnace chamber, which shall be maintained at a temperature of 950°C ± 20°C. Regulation of the temperature to within the prescribed limits is critical. After the more rapid discharge of volatile matter has subsided as shown by the disappearance of the luminous flame or after heating for two or three minutes, tap the cover lightly to more perfectly seal the crucible and thus guard against the admission of air. After heating for exactly seven

minutes, remove the crucible from the furance, and without disturbing the cover, allow it to cool. Weigh as soon as cold. The percentage loss of weight minus the percentage moisture equals the volatile matter.

4. Ash content

Ash is determined by weighing the residue remaining after burning the sample under rigidly controlled conditions of sample weight, temperature, time and atmosphere. Wherever sample conditions are suitalbe ASTM D3174-73 or ISO is followed.

4.1 Apparatus

(a) TGA - STONE model 7060 TGA analyzer.

(b) Furnace - electric muffle furnace with adequate air circulation and provided with temperature controller at 750°C and 950°C.

(c) Capsules - Identical to those used in evaluating moisture content.

4.2 Procedure

(1) For samples weighing less than one gram it is necessary to resort to thermogravimetric analysis for evaluating the ash content of the sample.

(2) For samples weighing one gram or more, it is feasible to use ASTM or ISO procedures. Transfer approximately one gram of the sample to a weighed porcelain capsule and quickly establish the weight to the nearest 0.1 mg. Place the porcelain capsule containing the sample in a cold muffle furnace and gradually heat to redness at such a rate as

to avoid mechanical loss from too rapid expulsion of volatile matter. Finish the ignition to constant weight (0.001) at a temperature between 700° and 750°C. Cool in a desiccator over desiccant, and weigh as soon as cold.

5. Carbon and hydrogen content

The determination of carbon and hydrogen is made by burning a weighed quantity of sample in a closed system and fixing the products of combustion in an absorption train. ASTM procedure D3176 or ISO is followed.

5.1 Apparatus and procedure

Perkin-Elmer Model 240 Elemental Analyzer - The Model 240 elemental Analyzer accurately determines the carbon, hydrogen and nitrogen content of organic compounds by detecting and measuring their combustion products (CO_2, H_2O, and N_2). Combustion occurs in pure oxygen under static conditions. The combustion products are then analyzed automatically in a self-integrating, steady-state, thermal conductivity analyzer, which eliminates the tedious classical gravimetric-analysis which requires weighing of adsorption traps. Results are records in bar graph form on a 0.1 mV recorder.

Three systems in the Elemental Analyzer perform the determinations: these are the combustion train; the analytical system; and the electronics. Each system is in a separate compartment of the instrument to ensure optimum operating conditions.

The combustion train and the analytical system are shown in a simplified configuration in Fig. 1. A pure oxygen supply is required for sample

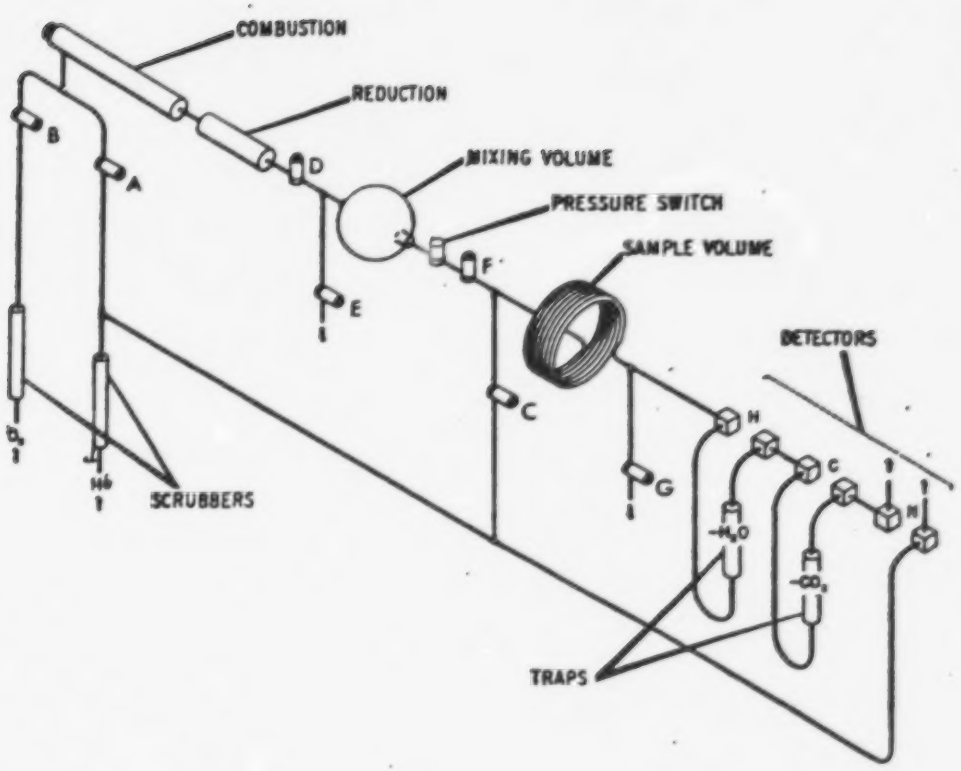
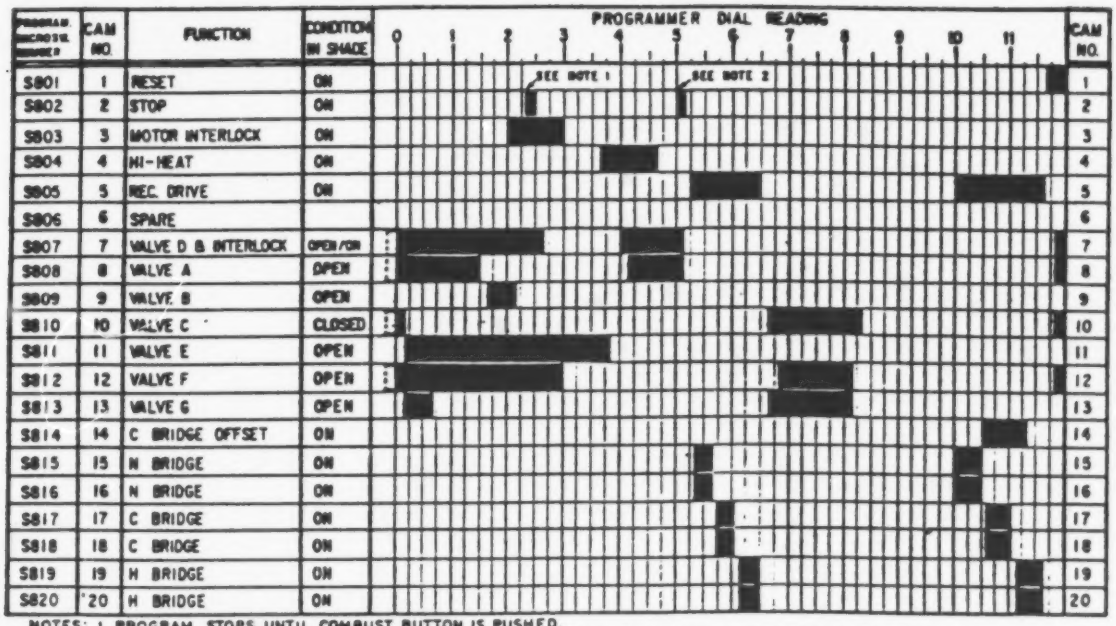


Fig. 1: Simplified diagram of combustion train and analytical system

combustion. Helium is used to carry the combustion products from the combustion train, through the analytical system, to atmosphere. Gas flows are determined by solenoid valves A through G, controlled by a cam-operated programmer in the sequence shown in Fig. 2.

The combustion train which is shown in Fig. 3, includes independently heated combustion and reduction furnaces, each with the appropriate reaction tube. The convenient sample fitting plug at the end of the combustion tube facilitates rapid introduction of samples into the train for combustion.

The analytical system consists of a mixing volume (in which the sample combustion products CO_2, H_2O), and nitrogen are mixed with helium to a homogeneous, equilibrated mixture), a pressure switch, a sample volume, detectors and adsorption traps. Three pairs of thermal conductivity cells, in series, are used for detection, one pair each for water, carbon dioxide and nitrogen. The platinum filaments of each cell pair are connected differentially in a bridge circuit so that any difference in the contents of the two cells will result in an electrical signal. A magnesium perchlorate trap between the first pair of cells adsorbs any water from the gas mixture before it enters the second cell so that the signal obtained from the corresponding bridge circuit is proportional to the amount of water removed. Likewise, an adsorbing trap between the second pair of cells detects nitrogen by comparing the thermal conductivity of the remaining sample gas with that of pure helium. The output signals from the bridge circuits are applied, through adjustable attenuators, to the 1.0 mV recorder. With the attenuators, the analyst can control the scale used in recording each combustion product.



PROGRAM SOLENOID NUMBER	CAM NO	FUNCTION	CONDITION IN SHADE	CAM NO.
S801	1	RESET	ON	1
S802	2	STOP	ON	2
S803	3	MOTOR INTERLOCK	ON	3
S804	4	HI-HEAT	ON	4
S805	5	REC. DRIVE	ON	5
S806	6	SPARE		6
S807	7	VALVE D & INTERLOCK	OPEN/CR	7
S808	8	VALVE A	OPEN	8
S809	9	VALVE B	OPEN	9
S810	10	VALVE C	CLOSED	10
S811	11	VALVE E	OPEN	11
S812	12	VALVE F	OPEN	12
S813	13	VALVE G	OPEN	13
S814	14	C BRIDGE OFFSET	ON	14
S815	15	N BRIDGE	ON	15
S816	16	N BRIDGE	ON	16
S817	17	C BRIDGE	ON	17
S818	18	C BRIDGE	ON	18
S819	19	H BRIDGE	ON	19
S820	20	H BRIDGE	ON	20

NOTES: 1. PROGRAM STOPS UNTIL COMBUST BUTTON IS PUSHED.
2. PROGRAM STOPS UNTIL PRESSURE IN MIXING CHAMBER RISES TO APPROXIMATELY 1500 MM Hg. THEN PRESSURE SWITCH S401 OPENS AND CAUSES SOLENOID VALVE D TO CLOSE AND THE PROGRAM TO RESTART.

Fig. 2: Model 240 elemental analyzer program

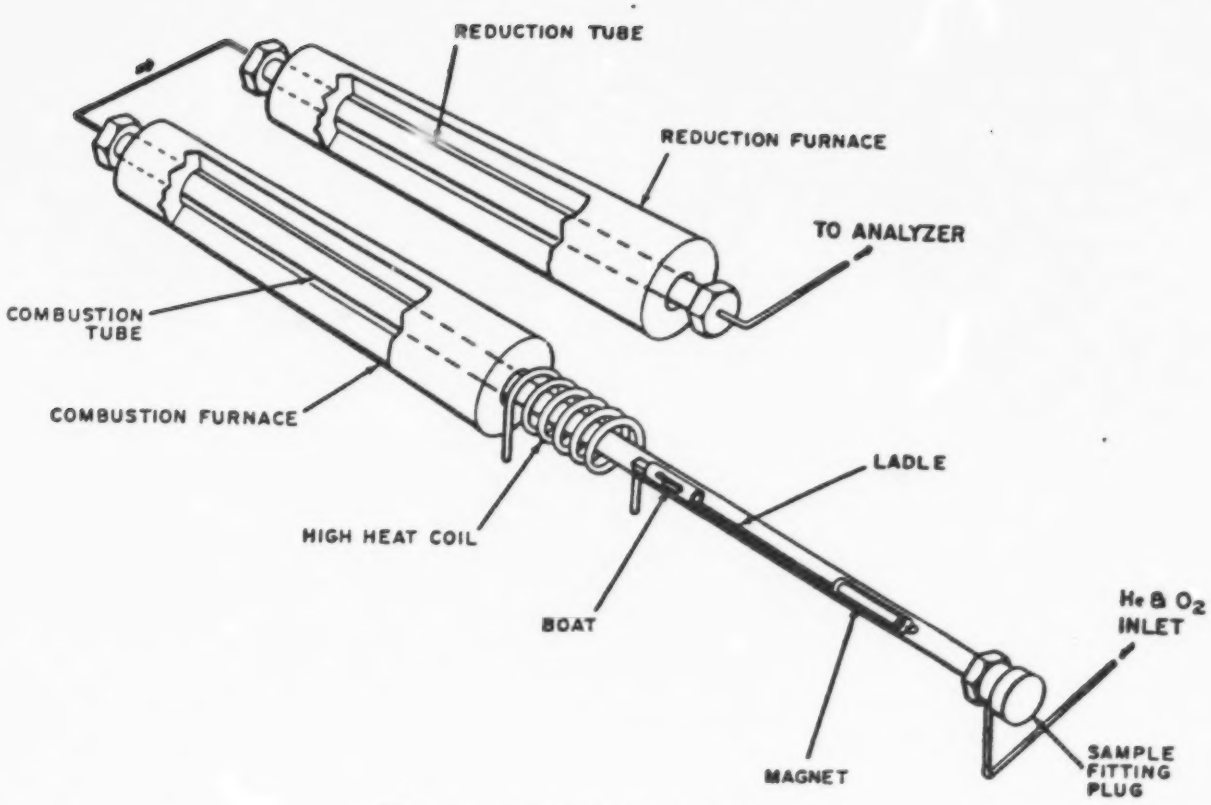


Fig. 3: Combustion train

6. Calorific value

Calorific value is determined in this method by burning a weighed sample in an adiabatic oxygen bomb calorimeter under controlled conditions. The calorific value is computed from temperature observations made before and after combustion, making proper allowance for thermochemical corrections. Procedures described under ASTM D2105-66 or ISO are followed. A PARR adiabatic bomb calirimeter complete with controller is used.

6.1 Procedure

(1) Standardization

Determine the water equivalent of the calorimeter as the average of a series of 10 individual runs, made over a period of not less than three days nor more than five days using NBS benzoic acid in place of the sample. To be acceptable, the standard deviation of the series shall be 6.86 kJK^{-1} or less.

(2) Restandardization

The standard water equivalent must be checked after changing any part of the calorimeter and at least once a month. If a single new standard value exceeds the old standard by 6.3 kJK^{-1}, the old standard is suspect and requires a second test.

(3) Testing

Thoroughly mix the analysis sample and carefully weigh approximately one gram of it into the crucible in which it is to be burned. The sample shall be weighed to the nearest 0.1 mg.

Add 1.0 ml of water to the bomb by a pipette. Before adding this water, rinse the bomb, invert to drain, and leave undried.

Connect a measured length of firing wire to the ignition terminals, with

enough slack to allow the firing wire to maintain contact with the sample.

Charge the bomb with oxygen to a pressure between 20 and 30 bar. This pressure must remain the same for each calibration and for each calorific determination. Adjust the calorimeter water temperature to between 1.0° - 1.4°C (2.0 to 2.5°F) below room temperature. Use the same weight measured to 0.5 g of water in each experiment.

Transfer the bomb to the calorimeter, check that it is gas-tight, and connect it to the firing circuit. Place the stirrers, thermometers and cover in position. Turn on control switch. (Stirrer is to be in continuous operation throughout the determination). If the temperature difference between the calorimeter and jacket is more than 2°C then the temperature is adjusted manually: all subsequent adjustments are done automatically. After five minutes, the "initial temperature" is recorded.

Fire the bomb sample. Take calorimeter temperature readings at one minute intervals until the same temperature (within one tenth of the smallest thermometer subdivision) is observed for successive readings. Record this as the "final temperature".

Start timer and wait eight minutes. Remove the bomb and release the pressure at a uniform rate such that the operation will require not less than one minute. Examine the bomb interior and discard the test if unburned sample or sooty deposits are found. Wash the interior of the bomb with distilled water containing the titration indicator, until the washings are free of acid, and titrate the washings with standard carbonate solution. Remove and weigh the combined pieces of unburned firing wire and subtract from the original weight to determine the wire consumed in firing. Determine the sulphur content of the sample.

7. Sulphur content

Combustion of the sample during the test for evaluating its calorific value provides a convenient way to oxidize and prepare the sample for precipitation of the sulphur (both organic and inorganic forms) as $BaSO_4$. Thus, the equipment used is identical to that for evaluating calorific value.

7.1 Procedure

The sample is treated as in the calorific procedure following all test conditions and precautions.

Let the bomb stand in the calorimeter for not less than five minutes after firing. Remove the bomb from the calorimeter water and open the valve carefully to allow gases to escape at an even rate, allowing at least one minute to reach room pressure. Carefully wash all parts of the interior of the bomb, including the capsule, with a fine jet of water containing methyl orange until no reaction is noted. Collect the washings in a 250 ml beaker and titrate with standard sodium carbonate solution to obtain "acid correction" for the heating value.

Adjust the pH to 5.5 - 7.0 with NH_4OH, heat the solution to boiling, and filter through qualitative paper. Wash the residue and paper thoroughly, five to six times with hot water. Add 1.0 ml of saturated bromine water and sufficient HCl to make the solution slightly acid. Boil the solution to expel excess bromine and adjust the acidity to 1.0 ml excess of HCl. Boil again, and while stirring constantly, slowly add from a pipette 10 ml or more of $BaCl_2$ solution: the $BaCl_2$ solution must be in excess. Continue boiling for

15 minutes and allow to stand for two hours or overnight at a temperature just below boiling.

Filter through an ashless paper and wash with hot water until silver nitrate shows no precipitate with a drop of the filtrate. Place the wet filter containing the precipitae of $BaSO_4$ in a tared platinum crucible, allowing a free access of air to the paper. Ignite by raising the temperature slowly. Ignite at 925°C to constant weight.

A blank must be determined using the method outlined above.

3. Chemical analysis of ash

Ash samples are fused with Shapiro's mixture in a graphite crucible , leached with nitric acid and filtered into a volumetric flask. This solution is then used for evaluating the concentration of Al_2O_3, CaO, MgO, Na_2O, K_2O, Fe_xO_3 by atomic absorption while the concentration of SiO_2 and TiO_2 is determined by colorimetric and spectrophotometric means. Minor elements (B, Ba, Be, Bi, Cr, Ga, La, Mo, Sc, Sn, Sr, V, Y, Yb and Zn) are determined by emmission spectrographs.

3.1 Apparatus

(a) JARRELL - ASH 810, Atomic absorption unit.

(2) SPECTRONIC 100 - Bausch and Lomb spectrometer.

(3) JARRELL - ASH 3.4 Ibert spectrograph.

3.2 Procedure

Samples are fused with Shapiro's mixture in a graphite crucible, leached with nitric acid and filtered into a volumetric flask. This solution is

diluted 1:10 for the determination of silica by colorimetric analysis, using the Molybdenum blue method. Strontium is added to supress ionization and chemical interferences. Al_2O_3, CaO, MgO, Na_2, K_2O, Fe_2O_3, are all determined by atomic absorption. CaO, MgO, and Al_2O_3 require a nitrous oxide-acetylene flame, while Na_2O, K_2O, and Fe_2O_3, are analyzed by an air-acetylene flame. Zero is set with a reagent blank on both atomic absorbtion and the spectrophotometer.

Two international standards of composition similar to the unknown samples are included with each set of analyses. The analytical results for each element are ratioed to the two international standards in order to overcome matrix effects. The standards used are those supplied by the U.S. Geological Survey and CANMET.

For determination of minor elements (B, Ba, Be, Bi, Cr, Ga, La, Mo, Sc, Sn, Sr, V, Y, Yb and Zn), the sample is mixed with graphite and a buffer of lithium and potassium. As internal standards Eu and Pd are added to the mixture. It is then volatilized and excited in an air-jet controlled D.C. arc. It is dispersed in a 3.4 meter Ibert Spectrograph with the spectra recorded on photographic plates. Conversions from densitometer readings through relative intensities to concentrations by a Seidel calculating board and analytical working curves. The concentration ranges for some of the above elements are not quite broad enough and are done by alternative methods.

APPENDIX V:

In-flame measurements

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1. General

An evaluation of the combustion and heat transfer characteristics from a flame requires a number of in-flame measurements to be made. Flames are "hostile" environments yet the measurements need to be made with a high degree of precision. This appendix describes in detail the various in-flame measurement techniques and procedures used.

2. Flame temperatures

Heat transfer by radiation is dependent upon temperature to the fourth power: it is, therefore, important that measurements of temperature are made with a high degree of accuracy.

Flame temperatures within the combustion chamber are measured using a Land type SU4 water-cooled suction pyrometer. The suction pyrometer, shown in Figure 1, is fitted with a type B (Pt-30% Rh/Pt-6% Rh) thermocouple. The hot gases are drawn across the thermocouple which is housed in an alumina sheath: suction is provided by means of a steam ejector. The tip of the probe is protected by a silicon carbide coated alumina shield with a side entry for the hot gases to be drawn into. Sampling is carried out in the wake of the probe to minimize blockage from particulates.

2.1 Determination of the efficiency

It is first necessary to determine the efficiency of the suction pyrometer. This is done by inserting the probe into the hot gases and

monitoring the output of the thermocouple. The suction is then increased until a steady thermocouple output is achieved. This represents the maximum (suction) temperature (T_s). The suction is then reduced so as to decrease the gas velocity to one quarter of that which produced the maximum temperature, (T_s). This is achieved by reducing the suction until the pressure drop across the orifice plate in the suction line is 1/16 of its maximum value. This temperature is monitored ($T_{0.25}$). The suction is then reduced to zero and the temperature monitored is termed the non-suction temperature (T_{ns}). From these measurement one calculates the shape factor (S) from:

$$S = (T_s - T_{ns})/(T_s - T_{0.25}) \qquad (1)$$

The efficiency (e) is determined from a graph of efficiency vs. shape factor shown in Figure 2.

2.2 Routine temperature measurements

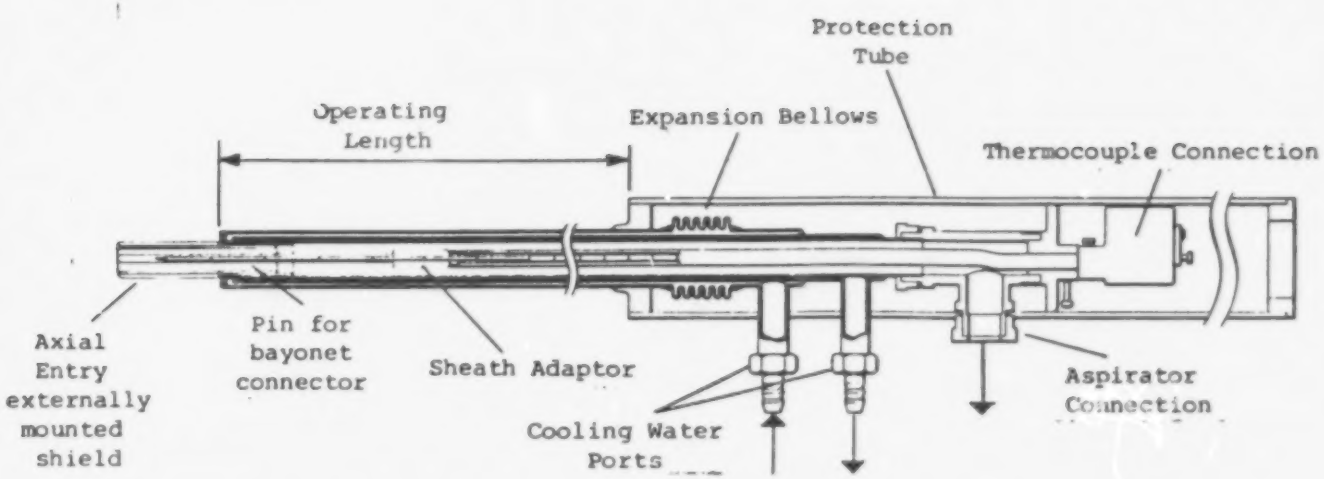
The suction pyrometer is inserted into the hot gases at the desired measurement location. Both the suction (T_s) and non-suction (T_{ns}) temperature are measured. The gas temperature (T_g) is calculated from:

$$T_g = T_s + (1 - e)(T_s - T_{ns}) \qquad (2)$$

2.3 Rapid temperature measurements

Invariably the efficiency of the suction pyrometer is found to be very nearly 100%; in such cases the last term of Eq (2) is very small and the true gas temperature (Tg) is almost the same as the suction temperature (Ts). This enables rapid temperature measurements still with a high degree

Figure 1: Land type SU4 suction pyrometer



APPENDIX VI

Steam Flow Measurement

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1. General

The atomisation air flow rate is easily monitored through the use of readily available variable-area glass tube rotameters. However, steam flow measurement, particularly at low flow rates, is not that simple. To overcome this difficulty, a steam flow meter, particularly for use in low flow applications, was designed and implemented at the Centre. Also, a steam quality meter was installed. Together, these two instruments enable the monitoring of atomization steam flow and quality and each is briefly described herein.

2. Steam flow measurement

A square-edged orifice plate is mounted in a 2 inch insulated steam line generating a pressure drop that is detected by a differential pressure transducer. The transducer output is monitored on a data logger and is calibrated to give a direct measure of steam flowrate/[kg s^{-1}].

3. Steam quality measurement

An Ellison U Path Steam Calorimeter (Model 905) is used to measure steam quality and operates accurately down to a minimum steam quality of 0.96 and minimum line pressure of 550 kPa. The following equation is used to determine the percentage of moisture in the steam:

$$m = 100[H-h-K(T-t)]/L \qquad (1)$$

where: m = percent moisture/[%]

H = enthalpy of steam in line/[$Wm^{-1}\ K^{-1}$]

h = enthalpy of steam in calorimeter/[$Wm^{-1}\ K^{-1}$]

K = specific heat of superheated steam/[-]

T = temperature of superheat in the calorimeter/[K]

t = temperature due to pressure in the calorimeter/[K]

L = latent heat in steam line/[$Wm^{-1}\ K^{-1}$]

The steam quality is determined from:

$$Q = 100 - m \qquad (2)$$

where: Q = steam quality/[%]

APPENDIX VII:

Raw gas data

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Gas Compositon Data for Test No. 1

Port 10 AXIAL LOCATION Z/L = 0.17 r/R = 1

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.79	3.74	0.180	0.033	0.431
12.77	3.74	0.183	0.033	0.285
12.83	3.74	0.182	0.033	0.298
12.79	3.74	0.181	0.033	0.298
12.73	3.74	0.178	0.033	0.305
12.89	3.74	0.176	0.032	0.296
12.70	3.74	0.176	0.032	0.290
12.83	3.74	0.174	0.032	0.403
12.79	3.74	0.175	0.032	0.436
12.77	3.74	0.173	0.032	0.421
12.82	3.74	0.177	0.032	0.381
12.79 ±0.05	3.74 ±0.00	0.178 ±0.003	0.032 ±0.001	0.349 ±0.064

Run 10 AXIAL LOCATION Z/L = 0.17, r/R = 0.17

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.02	3.74	0.186	0.038	0.183
12.92	3.74	0.187	0.037	0.177
12.94	3.74	0.184	0.037	0.185
12.92	3.74	0.178	0.036	0.200
12.91	3.74	0.180	0.036	0.183
12.93	3.74	0.179	0.036	0.248
12.89	3.74	0.181	0.035	0.265
12.81	3.74	0.184	0.036	0.287
12.87	3.74	0.185	0.036	0.295
12.91	3.74	0.187	0.037	0.320
12.84	3.74	0.187	0.036	0.347
12.93	3.74	0.186	0.037	0.388
12.91	3.74	0.184	0.036	0.257
±0.05	±0.00	±0.003	±0.001	±0.072

Part 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.35

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.75	3.74	0.185	0.036	0.537
12.70	3.74	0.183	0.035	0.472
12.69	3.74	0.182	0.035	0.479
12.66	3.74	0.181	0.034	0.484
12.74	3.74	0.183	0.034	0.475
12.75	3.74	0.179	0.035	0.497
12.61	3.74	0.183	0.034	0.544
12.71	3.74	0.179	0.034	0.642
12.79	3.74	0.179	0.034	0.638
12.77	3.74	0.179	0.034	0.635
12.69	3.74	0.179	0.034	0.630
12.74	3.74	0.180	0.034	0.652
12.72	3.74	0.181	0.034	0.557
±0.05	±0.00	±0.002	±0.001	±0.076

Port 1D AXIAL LOCATION Z/L = 0.17; r/R = 0.52

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.73	3.74	0.181	0.035	0.607
12.80	3.74	0.180	0.036	0.592
13.05	3.55	0.180	0.038	0.602
13.08	3.67	0.181	0.037	0.566
13.11	3.65	0.183	0.038	0.573
13.11	3.63	0.184	0.039	0.583
13.13	3.53	0.184	0.039	0.593
13.13	3.58	0.185	0.039	0.628
13.22	3.44	0.183	0.039	0.688
13.11	3.51	0.183	0.039	0.700
13.05 ±0.16	3.60 ±0.10	0.182 ±0.002	0.038 ±0.001	0.613 ±0.046

Port 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.78

CO_2	CO	SO_2 /[%]	NO_x	O_2
11.91	0.163	0.142	0.035	4.91
11.94	0.155	0.140	0.035	4.95
11.86	0.146	0.138	0.035	5.02
11.79	0.122	0.137	0.036	5.09
11.77	0.139	0.137	0.035	5.11
12.00	0.141	0.138	0.036	5.00
11.87	0.131	0.139	0.035	5.02
11.75	0.115	0.139	0.035	5.22
11.86 ±0.09	0.139 ±0.016	0.139 ±0.002	0.035 ±0.000	5.04 ±0.10

Port 2b AXIAL LOCATION Z/L = 0.36; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.55	0.048	0.088	0.027	5.09
12.56	0.051	0.090	0.027	5.00
12.56	0.063	0.110	0.028	4.48
12.65	0.050	0.116	0.029	4.37
12.65	0.054	0.113	0.030	4.26
12.70	0.066	0.107	0.030	4.34
12.62	0.040	0.099	0.030	4.37
12.71	0.076	0.094	0.030	4.35
12.81	0.052	0.094	0.030	4.23
12.57	0.041	0.094	0.030	4.33
12.60	0.054	0.096	0.030	4.37
12.52	0.027	0.098	0.030	4.45
12.69	0.049	0.104	0.030	4.43
12.73	0.039	0.125	0.030	4.29
12.64 ±0.08	0.051 ±0.012	0.102 ±0.011	0.029 ±0.001	4.45 ±0.26

Port 2b AXIAL LOCATION Z/L = 0.36; r/R = 0.17

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.93	0.141	0.130	0.032	4.09
12.91	0.135	0.131	0.032	3.99
12.88	0.117	0.134	0.032	3.98
12.88	0.167	0.134	0.032	3.96
12.99	0.180	0.136	0.031	3.88
12.98	0.121	0.136	0.032	3.89
12.96	0.163	0.137	0.032	3.84
12.83	0.119	0.138	0.032	3.96
12.98	0.159	0.138	0.032	3.77
12.94	0.101	0.138	0.032	3.74
12.91	0.122	0.138	0.032	3.79
13.01	0.139	0.136	0.032	3.73
12.94	0.137	0.136	0.032	3.77
12.93 ±0.05	0.139 ±0.023	0.136 ±0.003	0.032 ±0.000	3.88 ±0.11

Port 2b AXIAL LOCATION Z/L = 0.36; r/R = 0.35

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.49	0.247	0.141	0.034	3.36
13.53	0.358	0.145	0.034	3.00
13.58	0.436	0.148	0.034	2.78
13.57	0.380	0.148	0.034	2.72
13.56	0.364	0.146	0.034	2.79
13.59	0.378	0.147	0.034	2.73
13.69	0.406	0.148	0.034	2.59
13.60	0.411	0.148	0.034	2.65
13.60	0.411	0.145	0.034	2.62
13.73	0.448	0.147	0.035	2.43
13.69	0.492	0.146	0.034	2.56
13.61 ±0.08	0.394 ±0.063	0.146 ±0.002	0.034 ±0.000	2.75 ±0.25

Port 2b AXIAL LOCATION Z/L = 0.36; r/R = 0.52

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.19	0.701	0.152	0.036	2.11
14.21	0.674	0.152	0.036	2.06
14.28	0.752	0.157	0.037	1.61
14.28	0.750	0.157	0.036	1.50
14.32	0.709	0.158	0.036	1.40
14.26	0.622	0.157	0.036	1.48
14.22	0.742	0.158	0.037	1.46
13.85	0.264	0.156	0.036	1.61
14.20	0.459	0.152	0.038	1.78
14.19	0.488	0.151	0.037	1.85
14.18	0.436	0.153	0.037	1.78
14.18	0.472	0.154	0.037	1.89
14.20 ±0.12	0.589 ±0.100	0.155 ±0.003	0.037 ±0.001	1.71 ±0.24

Port 2b AXIAL LOCATION Z/L = 0.36; r/R = 0.70

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.35	0.362	0.156	0.039	1.73
14.35	0.365	0.156	0.039	1.67
14.28	0.338	0.157	0.038	1.69
14.37	0.345	0.158	0.039	1.57
14.45	0.403	0.159	0.039	1.42
14.34	0.353	0.157	0.039	1.48
14.48	0.456	0.157	0.039	1.37
14.56	0.506	0.158	0.039	1.18
14.45	0.401	0.155	0.038	1.30
14.32	0.370	0.155	0.038	1.44
14.41	0.373	0.154	0.038	1.61
14.48	0.398	0.157	0.038	1.53
14.40 ±0.08	0.389 ±0.049	0.157 ±0.001	0.039 ±0.001	1.50 ±0.17

Port 2b AXIAL LOCATION Z/L = 0.36; r/R = 0.87

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.83	0.069	0.148	0.034	2.43
12.49	0.050	0.133	0.033	4.07
12.30	0.043	0.131	0.032	4.57
12.41	0.053	0.129	0.032	4.89
12.29	0.058	0.128	0.032	5.03
11.92	0.041	0.128	0.030	5.11
12.20	0.044	0.130	0.032	4.96
12.19	0.042	0.129	0.032	5.12
11.99	0.051	0.129	0.031	4.99
12.25	0.047	0.133	0.032	5.02
12.16	0.042	0.134	0.032	5.02
12.22	0.055	0.133	0.032	5.09
12.27 ±0.24	0.050 ±0.008	0.132 ±0.005	0.032 ±0.001	4.69 ±0.77

Port 3b AXIAL LOCATION Z/L = 0.56; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
11.73	0 003	0.088	0.025	5.58
11.72	0.003	0.088	0.025	5.59
11.88	0.003	0.089	0.026	5.61
11.90	0.005	0.090	0.026	5.54
11.98	0.005	0.092	0.026	5.44
12.01	0.004	0.095	0.026	5.40
11.98	0.004	0.095	0.026	5.42
12.01	0.003	0.096	0.026	5.40
12.00	0.003	0.097	0.026	5.38
11.96	0.004	0.099	0.026	5.40
11.93 ±0.10	0.004 ±0.001	0.093 ±0.004	0.026 ±0.000	5.48 ±0.09

Port 4b AXIAL LOCATION Z/L = 0.74; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.16	0.003	0.083	0.025	5.13
12.14	0.002	0.084	0.025	5.14
12.21	0.003	0.088	0.026	5.15
12.18	0.004	0.089	0.025	5.13
12.17	0.004	0.087	0.025	5.14
12.23	0.004	0.090	0.026	5.05
12.23	0.004	0.090	0.025	5.07
12.24	0.003	0.091	0.026	5.07
12.31	0.002	0.092	0.026	4.98
12.30	0.002	0.093	0.026	4.96
12.29	0.001	0.101	0.026	4.91
12.30	0.002	0.0992	0.026	4.93
12.23 ±0.06	0.003 ±0.001	0.091 ±0.005	0.026 ±0.001	5.06 ±0.09

Port 5b AXIAL LOCATION Z/L = 0.90; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.71	0.001	0.107	0.027	5.03
12.71	0.002	0.108	0.028	4.93
12.72	0.001	0.119	0.028	4.45
12.80	0.002	0.123	0.029	4.23
12.76	0.002	0.106	0.027	4.48
12.77	0.002	0.098	0.027	4.27
12.84	0.003	0.104	0.028	4.17
12.71	0.004	0.092	0.027	4.82
12.76	0.003	0.096	0.027	4.41
12.75 ±0.06	0.002 ±0.001	0.106 ±0.010	0.028 ±0.001	4.53 ±0.33

BREECHING SECTION AXIAL LOCATION Z/L = 1.13; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.18	0.003	0.115	0.031	5.07
12.23	0.003	0.122	0.032	5.02
12.26	0.004	0.125	0.032	4.99
12.24	0.003	0.129	0.032	5.02
12.25	0.004	0.131	0.032	5.03
12.28	0.003	0.132	0.032	4.99
12.26	0.004	0.134	0.032	5.01
12.28	0.003	0.136	0.031	5.00
12.26	0.003	0.137	0.031	5.00
12.21	0.004	0.138	0.031	5.06
12.25 ±0.03	0.003 ±0.001	0.130 ±0.007	0.032 ±0.001	5.02 ±0.03

Gas composition data for Test No. 2

Port 1b AXIAL LOCATION Z/L = 0.17; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.52	2.89	0.142	0.026	1.09
13.54	2.74	0.140	0.026	1.17
13.48	2.55	0.139	0.026	1.25
13.38	2.72	0.136	0.026	1.31
13.46	2.94	0.136	0.025	1.41
13.56	2.74	0.142	0.026	1.11
13.44	2.85	0.142	0.025	1.21
13.52	2.44	0.141	0.027	1.22
13.56	2.24	0.140	0.027	1.38
13.50 ±0.06	2.68 ±0.23	0.140 ±0.002	0.026 ±0.001	1.24 ±0.11

Port 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.17

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.24	2.27	0.137	0.027	1.68
13.24	2.73	0.139	0.026	1.59
13.17	3.01	0.137	0.026	1.57
13.18	2.54	0.139	0.026	1.63
13.32	2.22	0.136	0.027	1.78
13.18	3.21	0.140	0.025	1.51
13.27	2.87	0.141	0.025	1.51
13.10	3.27	0.141	0.024	1.49
13.21 ±0.07	2.77 ±0.40	0.139 ±0.002	0.026 ±0.001	1.60 ±0.10

Port 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.35

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.19	3.46	0.144	0.024	1.21
13.17	3.17	0.146	0.026	1.16
13.21	3.23	0.146	0.025	1.26
13.24	2.93	0.144	0.026	1.31
13.16	2.62	0.141	0.027	1.55
13.34	2.07	0.139	0.028	1.62
13.28	2.50	0.140	0.027	1.59
13.20	2.75	0.139	0.026	1.61
12.91	3.58	0.142	0.025	1.50
12.98	3.50	0.141	0.025	1.54
12.97	3.74	0.147	0.023	1.10
13.15 ±0.14	3.05 ±0.52	0.143 ±0.003	0.026 ±0.001	1.40 ±0.20

Port 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.52

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.06	3.50	0.147	0.025	1.05
13.18	3.57	0.143	0.026	1.18
13.26	3.11	0.148	0.027	1.06
13.29	3.05	0.149	0.027	1.08
13.25	3.23	0.145	0.027	1.22
13.15	3.45	0.145	0.026	1.14
13.22	3.05	0.144	0.027	1.21
13.30	2.81	0.144	0.027	1.31
13.26	2.96	0.144	0.027	1.39
13.22 ±0.08	3.19 ±0.26	0.145 ±0.022	0.027 ±0.001	1.18 ±0.12

Port 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.70

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.67	2.21	0.149	0.031	1.11
13.57	2.46	0.148	0.031	1.09
13.61	1.89	0.144	0.031	1.11
12.77	0.274	0.123	0.033	3.38
12.79	0.273	0.118	0.033	3.95
12.75	0.250	0.117	0.032	4.12
12.67	0.269	0.114	0.032	4.24
12.70	0.249	0.116	0.032	4.21
12.68	0.230	0.113	0.033	4.28
12.65	0.227	0.113	0.033	4.34
13.01	0.359	0.116	0.033	3.81
12.93	0.357	0.118	0.033	3.60
12.98 ±0.40	0.754 ±0.873	0.124 ±0.014	0.032 ±0.001	3.27 ±1.34

Port 2b AXIAL LOCATION Z/L = 0.36; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.18	0.006	0.119	0.028	4.91
11.96	0.004	0.118	0.028	5.13
12.11	0.003	0.115	0.029	5.13
12.12	0.003	0.115	0.029	5.14
12.40	0.004	0.116	0.029	4.78
12.37	0.003	0.116	0.030	4.69
12.39	0.002	0.113	0.030	4.63
12.38	0.005	0.112	0.030	4.70
12.21	0.005	0.107	0.030	4.92
11.98	0.007	0.104	0.028	5.15
12.21 ±0.17	0.004 ±0.002	0.114 ±0.005	0.029 ±0.001	4.92 0.21

Port 2b AXIAL LOCATION Z/L = 0.36; r/R = 0.17

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.08	0.006	0.099	0.029	5.04
11.96	0.007	0.096	0.029	5.15
11.94	0.002	0.094	0.028	5.22
12.03	0.003	0.092	0.028	5.19
11.77	0.014	0.090	0.028	5.42
11.97	0.008	0.080	0.028	5.41
11.94	0.016	0.081	0.028	5.34
11.79	0.003	0.081	0.028	5.46
12.08	0.013	0.081	0.028	5.11
11.78	0.004	0.079	0.028	5.34
11.93 ±0.12	0.008 ±0.005	0.087 ±0.008	0.028 ±0.000	5.27 ±0.15

Port 2b AXIAL LOCATION Z/L = 0.36; r/R = 0.35

CO_2	CO	SO_2 /[%]	NO_x	O_2
11.98	0.023	0.058	0.028	5.12
12.61	0.041	0.059	0.029	4.48
12.41	0.036	0.059	0.029	4.46
12.24	0.024	0.056	0.029	4.72
12.09	0.026	0.056	0.028	5.04
12.82	0.060	0.072	0.029	4.37
12.74	0.040	0.058	0.029	4.23
12.68	0.034	0.059	0.029	4.33
12.43	0.028	0.059	0.029	4.48
12.29	0.014	0.057	0.029	4.68
12.43 ±0.28	0.033 ±0.013	0.059 ±0.005	0.029 ±0.000	4.59 ±0.30

Port 2b AXIAL LOCATION Z/L = 0.36; r/R = 0.52

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.43	0.141	0.074	0.030	3.31
13.47	0.169	0.076	0.030	3.17
13.49	0.118	0.078	0.030	3.03
13.40	0.133	0.078	0.030	3.23
13.59	0.168	0.083	0.030	2.97
13.68	0.205	0.085	0.030	2.88
13.83	0.184	0.087	0.031	2.81
13.83	0.165	0.090	0.031	2.63
13.77	0.130	0.093	0.030	2.51
13.40	0.133	0.082	0.030	3.44
13.59 ±0.18	0.155 ±0.028	0.083 ±0.006	0.030 ±0.000	3.00 ±0.30

Port 2b AXIAL LOCATION Z/L = 0.36; r/R = 0.70

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.64	0.118	0.092	0.030	2.95
13.67	0.117	0.093	0.030	2.93
13.55	0.089	0.091	0.030	3.01
13.41	0.097	0.091	0.030	3.10
13.44	0.111	0.091	0.030	3.19
13.30	0.086	0.092	0.030	3.13
13.46	0.991	0.092	0.030	3.10
13.58	0.128	0.092	0.030	3.09
13.47	0.080	0.092	0.030	3.06
13.39	0.076	0.089	0.029	3.42
13.41	0.080	0.089	0.029	3.76
13.16	0.085	0.091	0.029	3.55
13.47	0.094	0.093	0.030	3.35
13.46 ±0.14	0.166 ±0.249	0.091 ±0.001	0.030 ±0.000	3.20 ±0.25

Port 2b AXIAL LOCATION Z/L = 0.36; r/R = 0.87

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.71	0.042	0.082	0.026	4.44
12.40	0.038	0.079	0.027	4.80
12.45	0.050	0.077	0.026	5.03
12.66	0.033	0.070	0.027	4.87
12.02	0.020	0.076	0.027	5.31
12.62	0.060	0.075	0.027	5.38
12.64	0.054	0.077	0.027	5.16
12.04	0.032	0.078	0.026	5.25
12.64	0.086	0.083	0.027	4.40
12.13	0.037	0.079	0.061	4.72
12.43 ±2.27	0.045 ±0.018	0.079 ±0.003	0.030 ±0.011	4.94 ±0.35

Port 3b AXIAL LOCATION Z/L = 0.56; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.50	0.004	0.113	0.029	4.65
12.57	0.003	0.116	0.029	4.49
12.71	0.003	0.118	0.029	4.90
11.68	0.002	0.113	0.028	5.01
11.83	0.002	0.112	0.029	5.37
12.04	0.002	0.113	0.029	5.38
12.06	0.001	0.115	0.029	5.09
11.84	0.001	0.112	0.029	5.21
11.65	0.002	0.114	0.028	5.54
11.70	0.003	0.111	0.028	5.69
12.06 ±0.40	0.002 ±0.001	0.114 ±0.002	0.029 ±0.000	5.08 ±0.44

Port 4b AXIAL LOCATION Z/L = 0.74; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.09	0.001	0.098	0.028	4.98
12.26	0.002	0.100	0.029	4.89
12.38	0.003	0.104	0.029	4.77
12.53	0.003	0.107	0.029	4.61
12.59	0.002	0.107	0.029	4.47
12.56	0.002	0.109	0.029	4.43
12.55	0.002	0.109	0.029	4.40
12.67	0.002	0.110	0.030	4.34
12.67	0.001	0.112	0.030	4.31
12.62	0.002	0.120	0.030	4.28
12.49 ±0.19	0.002 ±0.001	0.108 ±0.006	0.029 ±0.001	4.55 ±0.25

Port 5b AXIAL LOCATION Z/L = 0.90; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.99	0.001	0.108	0.029	3.73
12.96	0.000	0.109	0.029	3.68
12.81	0.001	0.107	0.029	3.85
12.85	0.002	0.106	0.029	3.98
12.64	0.003	0.107	0.028	4.23
12.79	0.003	0.107	0.029	4.15
13.00	0.002	0.111	0.029	3.90
13.07	0.002	0.111	0.030	3.73
13.13	0.003	0.114	0.029	3.65
13.18	0.002	0.114	0.029	3.56
12.94 ±0.17	0.002 ±0.001	0.109 ±0.003	0.029 ±0.000	3.85 ±0.02

BREECHING AXIAL LOCATION Z/L = 1.13; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
11.53	0.003	0.109	0.028	5.70
11.59	0.003	0.109	0.028	5.64
11.58	0.003	0.092	0.028	5.63
11.59	0.002	0.152	0.028	5.59
11.63	0.002	0.145	0.028	5.58
11.74	0.002	0.156	0.028	5.46
11.84	0.002	0.111	0.028	5.33
11.74	0.001	0.111	0.028	5.26
11.66	0.001	0.110	0.028	5.36
11.55	0.001	0.092	0.028	5.51
11.65 ±0.10	0.002 ±0.001	0.119 ±0.024	0.028 ±0.000	5.51 ±0.15

Gas composition data for Test No. 3

PORT 1b AXIAL LOCATION Z/L = 0.17; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.26	0.018	0.039	0.071	4.50
14.30	0.017	0.041	0.072	3.95
14.39	0.017	0.045	0.072	3.82
14.17	0.018	0.044	0.071	3.99
14.31	0.016	0.047	0.070	4.02
14.18	0.018	0.047	0.071	4.02
14.24 ±0.10	0.017 ±0.001	0.044 ±0.003	0.071 ±0.001	4.05 ±0.23

PORT 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.17

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.57	0.027	0.050	0.075	3.43
14.56	0.027	0.052	0.075	3.36
14.48	0.026	0.049	0.075	3.51
14.54	0.030	0.052	0.074	3.52
14.47	0.025	0.050	0.075	3.50
14.29	0.027	0.049	0.074	3.71
14.49 ±0.10	0.027 ±0.002	0.050 ±0.001	0.075 ±0.001	3.51 ±0.12

PORT 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.35

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.77	0.074	0.044	0.082	3.38
15.07	0.126	0.046	0.082	2.85
15.16	0.112	0.057	0.081	2.63
14.86	0.092	0.047	0.081	2.85
14.59	0.077	0.049	0.080	3.23
14.65	0.072	0.045	0.081	3.28
14.85	0.092	0.048	0.081	3.04
±0.23	±0.022	±0.005	±0.001	±0.30

PORT 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.52

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.65	0.124	0.042	0.080	2.92
14.50	0.110	0.039	0.080	3.20
14.27	0.084	0.037	0.080	3.54
14.63	0.110	0.035	0.080	3.28
14.63	0.145	0.035	0.079	3.10
14.73	0.175	0.036	0.078	2.92
14.57	0.125	0.037	0.080	3.04
±0.16	±0.032	±0.003	±0.001	±0.46

PORT 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.70

CO_2	CO	SO_2 /[%]	NO_x	O_2
11.03	0.082	0.018	0.059	7.31
11.05	0.080	0.017	0.059	7.64
10.97	0.082	0.018	0.058	7.60
11.13	0.075	0.018	0.061	7.76
11.25	0.069	0.018	0.061	7.49
11.04	0.080	0.018	0.049	7.53
11.08 ±0.10	0.078 ±0.005	0.018 ±0.000	0.060 ±0.001	7.56 ±0.15

PORT 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.87

CO_2	CO	SO_2 /[%]	NO_x	O_2
10.25	0.091	0.014	0.050	7.79
10.95	0.076	0.010	0.052	7.96
10.69	0.080	0.012	0.051	8.01
10.74	0.078	0.011	0.051	8.13
10.70	0.074	0.011	0.053	8.29
10.69	0.073	0.011	0.052	8.02
10.67 ±0.23	0.079 ±0.007	0.012 ±0.001	0.052 ±0.001	8.03 ±0.17

PORT 2b AXIAL LOCATION Z/L = 0.35; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.38	0.012	0.066	0.072	3.80
14.29	0.012	0.071	0.072	3.74
14.27	0.012	0.071	0.073	3.75
14.20	0.011	0.074	0.072	3.77
14.14	0.011	0.073	0.071	3.93
14.42	0.011	0.074	0.072	3.61
14.28 ±0.11	0.012 ±0.001	0.072 ±0.003	0.072 ±0.001	3.77 ±0.10

PORT 2b AXIAL LOCATION Z/L = 0.35; r/R = 0.17

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.40	0.013	0.071	0.076	3.60
14.36	0.013	0.070	0.076	3.56
14.88	0.015	0.074	0.078	3.03
14.64	0.013	0.066	0.077	3.04
14.57	0.013	0.071	0.077	3.19
14.61 ±0.21	0.014 ±0.001	0.068 ±0.006	0.077 ±0.001	3.22 ±0.29

PORT 2b AXIAL LOCATION Z/L = 0.35; r/R = 0.35

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.80	0.017	0.069	0.082	2.88
14.78	0.017	0.066	0.082	2.97
14.69	0.017	0.065	0.091	3.06
14.47	0.015	0.065	0.080	3.33
14.49	0.016	0.063	0.080	3.42
14.52	0.016	0.065	0.080	3.21
14.63 ±0.15	0.016 ±0.001	0.066 ±0.002	0.081 ±0.001	3.15 ±0.21

PORT 2b AXIAL LOCATION Z/L = 0.35; r/R = 0.52

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.65	0.017	0.069	0.082	3.31
14.47	0.018	0.067	0.084	3.34
14.54	0.019	0.065	0.084	3.28
14.58	0.019	0.064	0.084	3.26
14.50	0.019	0.061	0.084	3.25
14.52	0.019	0.055	0.084	3.28
14.54 ±0.06	0.019 ±0.001	0.064 ±0.005	0.084 ±0.001	3.20 ±0.03

PORT 2b AXIAL LOCATION Z/L = 0.35; r/R = 0.70

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.26	0.022	0.055	0.083	3.70
14.21	0.025	0.063	0.081	3.53
14.26	0.022	0.056	0.082	3.66
14.36	0.023	0.058	0.083	3.68
14.21	0.023	0.057	0.082	3.75
14.20	0.021	0.057	0.082	3.67
14.25 ±0.06	0.023 ±0.001	0.058 ±0.003	0.082 ±0.001	3.67 ±0.07

PORT 2b AXIAL LOCATION Z/L = 0.35; r/R = 0.87

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.11	0.024	0.037	0.065	6.82
11.52	0.025	0.036	0.062	7.21
11.91	0.024	0.038	0.063	7.33
12.10	0.024	0.039	0.063	7.23
10.60	0.028	0.036	0.058	7.74
11.94	0.024	0.039	0.062	7.31
11.70 ±0.58	0.025 ±0.002	0.038 ±0.001	0.062 ±0.002	7.27 ±0.30

PORT 3b AXIAL LOCATION Z/L = 0.53; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.14	0.008	0.067	0.068	4.15
14.18	0.007	0.052	0.068	4.09
14.17	0.008	0.051	0.069	4.14
14.16	0.007	0.052	0.068	4.12
14.20	0.007	0.053	0.069	4.05
14.13	0.007	0.053	0.068	4.15
14.16 ±0.21	0.007 ±0.000	0.055 ±0.006	0.068 ±0.001	4.12 ±0.04

PORT 3b AXIAL LOCATION Z/L = 0.53; r/R = 0.17

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.62	0.009	0.056	0.074	3.58
14.74	0.010	0.058	0.075	3.35
14.78	0.010	0.060	0.075	3.29
14.87	0.010	0.061	0.076	3.16
14.55	0.009	0.057	0.074	3.39
14.52	0.009	0.060	0.074	3.58
14.68 ±0.14	0.010 ±0.001	0.059 ±0.002	0.075 ±0.001	3.39 ±0.17

PORT 3b AXIAL LOCATION Z/L = 0.53; r/R = 0.35

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.88	0.010	0.058	0.080	3.11
14.90	0.010	0.058	0.080	3.06
14.97	0.010	0.059	0.081	3.06
15.04	0.011	0.059	0.081	2.90
14.92	0.010	0.059	0.080	2.97
14.92	0.010	0.061	0.080	3.01
14.94 ±0.06	0.010 ±0.000	0.059 ±0.001	0.080 ±0.001	3.02 0.08

PORT 3b AXIAL LOCATION Z/L = 0.53; r/R = 0.52

CO_2	CO	SO_2 /[%]	NO_x	O_2
15.33	0.014	0.056	0.081	2.56
15.34	0.014	0.057	0.081	2.62
15.27	0.014	0.057	0.081	2.63
15.19	0.013	0.056	0.080	2.72
14.95	0.012	0.054	0.078	2.89
15.17	0.012	0.056	0.080	2.76
15.21 ±0.15	0.013 ±0.001	0.056 ±0.001	0.080 ±0.001	2.70 ±0.12

PORT 3b AXIAL LOCATION Z/L = 0.53; r/R = 0.70

CO_2	CO	SO_2 /[%]	NO_x	O_2
15.35	0.015	0.091	0.080	2.56
15.56	0.012	0.091	0.081	2.31
15.73	0.013	0.094	0.081	2.07
15.57	0.014	0.086	0.080	2.09
15.54	0.012	0.085	0.080	2.18
15.36	0.012	0.089	0.079	2.36
15.52 ±0.14	0.013 ±0.001	0.089 ±0.003	0.080 ±0.001	2.26 ±0.19

PORT 3b AXIAL LOCATION Z/L = 0.53; r/R = 0.87

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.53	0.011	0.083	0.071	3.13
14.78	0.009	0.084	0.073	3.25
14.66	0.010	0.083	0.072	3.39
14.65	0.010	0.086	0.073	3.17
14.84	0.010	0.086	0.072	3.13
14.95	0.011	0.085	0.072	3.25
14.74 ±0.15	0.010 ±0.001	0.085 ±0.001	0.072 ±0.001	3.22 ±0.10

PORT 4b AXIAL LOCATION Z/L = 0.73; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.41	0.006	0.071	0.065	3.80
14.41	0.005	0.061	0.065	3.84
14.44	0.005	0.068	0.065	3.81
14.35	0.005	0.066	0.065	3.86
14.30	0.005	0.062	0.064	3.94
14.41	0.005	0.068	0.065	3.89
14.39 ±0.05	0.005 ±0.000	0.066 ±0.004	0.065 ±0.000	3.86 ±0.05

PORT 5b AXIAL LOCATION Z/L = 0.89; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
15.21	0.005	0.059	0.065	2.81
15.24	0.005	0.059	0.065	2.80
15.07	0.005	0.060	0.065	2.93
15.12	0.005	0.064	0.065	2.91
15.19	0.005	0.073	0.065	2.83
15.08	0.005	0.070	0.065	2.89
15.15 ±0.07	0.005 ±0.000	0.064 ±0.006	0.065 ±0.000	2.86 ±0.06

BREECHING AXIAL LOCATION Z/L = 1.21; r/R = 0

INITIAL TEST

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.93	0.004	0.065	0.063	3.08
14.94	0.004	0.066	0.062	3.06
14.88	0.004	0.064	0.062	3.11
14.93	0.004	0.067	0.062	3.14
14.99	0.004	0.066	0.063	3.06
14.88	0.004	0.067	0.063	3.12
14.93 ±0.04	0.004 ±0.000	0.066 ±0.001	0.063 ±0.001	3.10 ±0.03

PORT 5b AXIAL LOCATION Z/L = 0.89; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
15.21	0.005	0.059	0.065	2.81
15.24	0.005	0.059	0.065	2.80
15.07	0.005	0.060	0.065	2.93
15.12	0.005	0.064	0.065	2.91
15.19	0.005	0.073	0.065	2.83
15.08	0.005	0.070	0.065	2.89
15.15 ±0.07	0.005 ±0.000	0.064 ±0.006	0.065 ±0.000	2.86 ±0.06

BREECHING AXIAL LOCATION Z/L = 1.21; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
14.93	0.004	0.065	0.063	3.08
14.94	0.004	0.066	0.062	3.06
14.88	0.004	0.064	0.062	3.11
14.93	0.004	0.067	0.062	3.14
14.99	0.004	0.066	0.063	3.06
14.88	0.004	0.067	0.063	3.12
14.93 ±0.04	0.004 ±0.000	0.066 ±0.001	0.063 ±0.001	3.10 ±0.03

Gas composition data for Test No. 4

Port 1b AXIAL LOCATION Z/L = 0.17; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
11.68	0.013	0.043	0.060	7.13
11.75	0.010	0.044	0.060	7.04
11.64	0.013	0.033	0.060	7.02
11.60	0.014	0.048	0.059	7.09
11.53	0.019	0.038	0.059	7.13
11.67	0.015	0.038	0.059	7.07
11.65 ±0.07	0.014 ±0.003	0.041 ±0.005	0.060 ±0.001	7.08 ±0.04

Port 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.17

CO_2	CO	SO_2 /[%]	NO_x	O_2
11.64	0.013	0.039	0.060	7.11
11.59	0.014	0.040	0.060	7.14
11.58	0.014	0.041	0.061	7.16
11.58	0.011	0.047	0.061	7.13
11.54	0.013	0.046	0.062	7.17
11.58	0.013	0.044	0.062	7.11
11.59 ±0.03	0.013 ±0.001	0.043 ±0.003	0.061 ±0.001	7.14 ±0.02

Port 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.35

CO_2	CO	SO_2 /[%]	NO_x	O_2
11.72	0.025	0.041	0.065	6.81
11.78	0.024	0.040	0.065	6.71
11.76	0.025	0.041	0.062	6.68
11.67	0.024	0.041	0.062	6.82
11.72	0.024	0.040	0.063	6.77
11.83	0.024	0.040	0.063	6.64
11.75 ±0.05	0.024 ±0.001	0.041 ±0.001	0.063 ±0.001	6.74 ±0.07

Port 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.52

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.25	0.173	0.026	0.079	4.61
13.11	0.130	0.027	0.078	4.69
13.08	0.118	0.027	0.078	4.93
12.97	0.107	0.027	0.078	5.04
12.93	0.125	0.026	0.079	5.08
13.03	0.153	0.026	0.079	4.85
13.06 ±0.11	0.134 ±0.024	0.027 ±0.001	0.079 ±0.001	4.87 ±0.18

Port 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.70

CO_2	CO	SO_2 /[%]	NO_x	O_2
9.46	0.266	0.030	0.062	8.88
9.42	0.286	0.028	0.061	8.88
9.48	0.274	0.029	0.062	9.01
9.70	0.265	0.029	0.063	8.78
10.03	0.257	0.029	0.063	8.45
9.74	0.253	0.029	0.061	8.57
9.64 ±0.23	0.267 ±0.013	0.029 ±0.001	0.062 ±0.001	8.76 ±0.21

Port 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.87

CO_2	CO	SO_2 /[%]	NO_x	O_2
7.98	0.421	0.033	0.050	11.63
6.61	0.432	0.030	0.041	11.78
6.25	0.418	0.025	0.041	12.64
6.42	0.424	0.023	0.041	12.68
6.71	0.429	0.024	0.046	12.72
7.87	0.432	0.024	0.051	11.36
6.97 ±0.75	0.426 ±0.006	0.027 ±0.004	0.045 ±0.005	12.14 ±0.61

Port 2b AXIAL LOCATION Z/L = 0.35; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
11.11	0.014	0.062	0.043	7.92
10.75	0.015	0.062	0.041	7.98
11.20	0.014	0.063	0.044	7.86
11.20	0.014	0.064	0.045	7.84
11.27	0.014	0.066	0.045	7.58
10.87	0.014	0.065	0.042	7.83
11.07 ±0.20	0.014 ±0.000	0.063 ±0.002	0.043 ±0.002	7.84 ±0.13

Port 2b AXIAL LOCATION Z/L = 0.35; r/R = 0.17

CO_2	CO	SO_2 /[%]	NO_x	O_2
11.29	0.012	0.066	0.046	7.54
11.23	0.013	0.065	0.046	7.64
10.98	0.013	0.063	0.044	7.75
11.14	0.012	0.064	0.044	7.71
10.89	0.014	0.066	0.043	8.00
10.25	0.021	0.064	0.036	7.96
10.96 ±0.38	0.014 ±0.003	0.064 ±0.001	0.043 ±0.004	7.77 ±0.18

Port 2b AXIAL LOCATION Z/L = 0.35; r/R = 0.35

CO_2	CO	SO_2 /[%]	NO_x	O_2
11.99	0.015	0.032	0.062	6.60
11.89	0.015	0.032	0.061	6.74
11.92	0.015	0.033	0.062	6.75
11.87	0.014	0.032	0.062	6.80
12.02	0.015	0.031	0.064	6.64
12.04	0.015	0.013	0.065	6.57
11.96 ±0.07	0.015 ±0.000	0.032 ±0.001	0.063 ±0.002	6.68 ±0.09

Port 2b AXIAL LOCATION Z/L = 0.35; r/R = 0.52

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.01	0.017	0.032	0.069	6.60
12.03	0.017	0.032	0.069	6.60
11.97	0.017	0.033	0.069	6.60
11.99	0.018	0.033	0.069	6.56
12.04	0.018	0.032	0.069	6.50
11.86	0.017	0.033	0.068	6.61
11.98 ±0.06	0.017 ±0.001	0.033 ±0.001	0.069 ±0.000	6.58 ±0.04

Port 2b AXIAL LOCATION Z/L = 0.35; r/R = 0.70

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.24	0.022	0.034	0.077	6.36
12.32	0.021	0.034	0.077	6.28
12.25	0.021	0.033	0.076	6.22
12.24	0.021	0.034	0.078	6.36
12.27	0.022	0.033	0.078	6.19
12.29	0.021	0.034	0.078	6.20
12.27 ±0.03	0.021 ±0.000	0.034 ±0.001	0.077 ±0.001	6.27 ±0.07

Port 2b AXIAL LOCATION Z/L = 0.35; r/R = 0.87

CO_2	CO	SO_2 /[%]	NO_x	O_2
10.67	0.037	0.029	0.058	8.28
10.56	0.038	0.029	0.058	8.23
10.54	0.037	0.030	0.057	8.20
10.52	0.039	0.030	0.057	8.24
10.42	0.039	0.034	0.055	8.22
10.62	0.034	0.033	0.058	8.21
10.56 ±0.08	0.037 ±0.002	0.031 ±0.002	0.057 ±0.001	8.23 ±0.02

Port 3b AXIAL LOCATION Z/L = 0.53; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.24	0.011	0.035	0.048	6.76
12.08	0.014	0.035	0.047	6.65
12.26	0.011	0.036	0.049	6.73
12.14	0.011	0.033	0.048	6.66
12.11	0.010	0.032	0.048	6.70
12.12	0.010	0.032	0.046	6.58
12.16 ±0.07	0.011 ±0.001	0.034 ±0.002	0.048 ±0.001	6.68 ±0.06

Port 3b AXIAL LOCATION Z/L = 0.53; r/R = 0.17

CO_2	CO	SO_2 /[%]	NO_x	O_2
11.71	0.012	0.041	0.042	7.29
11.80	0.012	0.038	0.042	7.19
11.89	0.013	0.040	0.043	7.23
11.76	0.013	0.042	0.043	7.25
11.78	0.013	0.041	0.043	7.22
11.86	0.013	0.043	0.044	7.20
11.80 ±0.06	0.013 ±0.001	0.041 ±0.002	0.043 ±0.001	7.23 ±0.03

Port 3b AXIAL LOCATION Z/L = 0.53; r/R = 0.35

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.84	0.011	0.036	0.056	6.02
13.05	0.011	0.037	0.057	5.77
13.08	0.012	0.039	0.058	5.66
13.28	0.011	0.037	0.058	5.45
13.23	0.012	0.030	0.055	5.49
12.87	0.011	0.027	0.054	5.81
13.06 ±0.18	0.011 ±0.001	0.034 ±0.005	0.056 ±0.002	5.70 ±0.21

Port 3b AXIAL LOCATION Z/L = 0.53; r/R = 0.52

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.48	0.013	0.060	0.056	6.37
12.52	0.012	0.062	0.055	6.36
12.48	0.013	0.064	0.055	6.36
12.47	0.013	0.064	0.055	6.34
12.45	0.013	0.063	0.054	6.39
12.37	0.013	0.063	0.053	6.42
12.46 ±0.05	0.013 ±0.000	0.063 ±0.002	0.055 ±0.001	6.37 ±0.02

Port 3b AXIAL LOCATION Z/L = 0.53; r/R = 0.70

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.27	0.014	0.071	0.061	5.40
13.44	0.014	0.070	0.062	5.26
13.38	0.014	0.070	0.062	5.32
13.35	0.013	0.069	0.062	5.38
13.29	0.013	0.071	0.062	5.53
13.27	0.016	0.071	0.063	5.47
13.33 ±0.07	0.014 ±0.001	0.070 ±0.001	0.062 ±0.001	5.39 ±0.10

Port 3b AXIAL LOCATION Z/L = 0.53; r/R = 0.87

CO_2	CO	SO_2 /[%]	NO_x	O_2
9.60	0.017	0.062	0.045	8.70
11.43	0.015	0.063	0.051	8.17
11.18	0.016	0.060	0.048	8.41
10.39	0.016	0.058	0.048	8.72
9.95	0.016	0.057	0.057	8.62
10.80	0.015	0.059	0.059	8.38
10.56 ±0.71	0.016 ±0.001	0.060 ±0.023	0.051 ±0.006	8.50 ±0.21

Port 4b AXIAL LOCATION Z/L = 0.73; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.92	0.006	0.094	0.058	5.74
12.78	0.006	0.095	0.058	5.91
12.82	0.007	0.096	0.057	5.91
12.87	0.006	0.097	0.057	5.82
12.86	0.007	0.095	0.057	5.83
12.86	0.006	0.093	0.058	5.83
12.85 ±0.04	0.006 ±0.001	0.095 ±0.001	0.058 ±0.001	5.84 ±0.06

Port 5b AXIAL LOCATION Z/L = 0.89; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.51	0.006	0.094	0.059	5.21
13.47	0.006	0.096	0.059	5.20
13.36	0.006	0.096	0.059	5.34
13.44	0.006	0.091	0.060	5.27
13.48	0.006	0.093	0.061	5.22
13.40	0.006	0.095	0.060	5.24
13.44 ±0.05	0.006 ±0.000	0.094 ±0.019	0.060 ±0.001	5.25 ±0.05

BREECHING AXIAL LOCATION Z/L = 1.21; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.64	0.005	0.054	0.062	4.84
13.58	0.004	0.054	0.060	4.94
13.56	0.004	0.052	0.060	4.98
13.56	0.005	0.051	0.059	5.00
13.59	0.005	0.083	0.060	4.96
13.66	0.007	0.085	0.062	4.84
13.60 ±0.04	0.005 ±0.001	0.063 ±0.016	0.061 ±0.000	4.93 ±0.07

Gas compositon data for Test No. 5

Port 1b AXIAL LOCATION Z/L = 0.17; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
9.92	0.021	0.052	0.042	8.77
10.26	0.017	0.051	0.042	8.70
10.21	0.018	0.051	0.042	8.75
10.20	0.016	0.050	0.043	8.72
10.20	0.016	0.050	0.043	8.70
10.29	0.018	0.050	0.042	8.68
10.18 ±0.13	0.018 ±0.002	0.051 ±0.001	0.042 ±0.001	8.72 ±0.03

Port 1b AXIAL LOCATION Z/L = 0.17; r/R = 0.35

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.08	0.026	0.046	0.070	6.59
11.92	0.024	0.047	0.068	6.67
11.74	0.025	0.046	0.068	6.87
11.82	0.025	0.045	0.068	6.87
12.10	0.024	0.041	0.069	6.73
12.50	0.027	0.042	0.072	6.23
12.03 ±0.27	0.025 ±0.001	0.045 ±0.002	0.069 ±0.002	6.66 ±0.23

Port 2b AXIAL LOCATION Z/L = 0.35; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
10.00	0.011	0.028	0.042	9.05
9.65	0.008	0.028	0.040	9.02
10.07	0.009	0.027	0.042	8.98
10.57	0.012	0.029	0.044	8.41
10.83	0.011	0.034	0.045	8.19
10.48	0.011	0.037	0.042	8.29
10.27 ±0.43	0.010 ±0.002	0.031 ±0.004	0.043 ±0.002	8.66 ±0.40

Port 2b AXIAL LOCATION Z/L = 0.35; r/R = 0.35

CO_2	CO	SO_2 /[%]	NO_x	O_2
11.16	0.022	0.032	0.055	7.70
11.08	0.019	0.032	0.055	7.73
10.94	0.019	0.032	0.055	7.89
10.94	0.016	0.032	0.055	8.00
11.05	0.016	0.033	0.056	7.84
11.15	0.018	0.033	0.057	7.77
11.05 ±0.09	0.018 ±0.002	0.032 ±0.001	0.056 ±0.001	7.82 ±0.11

Port 2b AXIAL LOCATION Z/L = 0.35; r/R = 0.70

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.74	0.085	0.034	0.065	5.88
12.86	0.083	0.034	0.065	5.59
13.02	0.130	0.035	0.065	5.33
13.03	0.115	0.036	0.065	5.22
12.58	0.071	0.035	0.065	5.62
12.64	0.072	0.035	0.065	5.70
12.81 ±0.19	0.093 ±0.024	0.035 ±0.001	0.065 ±0.000	5.56 ±0.24

Port 3b AXIAL LOCATION Z/L = 0.53; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.32	0.008	0.086	0.051	6.79
12.31	0.008	0.110	0.050	6.47
12.09	0.008	0.117	0.048	6.78
12.20	0.008	0.109	0.048	6.85
12.08	0.008	0.084	0.047	7.00
12.45	0.008	0.104	0.049	6.60
12.24 ±0.14	0.008 ±0.000	0.107 ±0.021	0.049 ±0.001	6.75 ±0.19

Port 3b AXIAL LOCATION Z/L = 0.53; r/R = 0.35

CO_2	CO	SO_2 /[%]	NO_x	O_2
11.28	0.010	0.054	0.045	7.74
11.10	0.011	0.054	0.045	7.75
11.27	0.011	0.056	0.047	7.93
11.25	0.011	0.058	0.046	7.93
11.23	0.010	0.065	0.046	7.92
11.32	0.010	0.064	0.047	7.85
11.24 ±0.07	0.010 ±0.001	0.058 ±0.005	0.046 ±0.001	7.86 ±0.08

Port 3b AXIAL LOCATION Z/L = 0.53; r/R = 0.52

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.70	0.012	0.065	0.064	4.89
13.90	0.012	0.066	0.064	4.69
13.75	0.013	0.065	0.062	4.66
13.49	0.014	0.064	0.060	4.95
13.33	0.013	0.063	0.059	5.14
13.31	0.013	0.063	0.058	5.28
13.58 ±0.24	0.013 ±0.001	0.064 ±0.001	0.061 ±0.002	4.94 ±0.24

Port 3b AXIAL LOCATION Z/L = 0.53; r/R = 0.70

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.66	0.012	0.065	0.064	5.04
13.70	0.012	0.065	0.064	4.89
13.90	0.012	0.066	0.064	4.69
13.75	0.013	0.065	0.062	4.66
13.49	0.014	0.064	0.060	4.95
13.33	0.013	0.063	0.059	5.14
13.64 ±0.20	0.013 ±0.001	0.065 ±0.001	0.062 ±0.002	4.90 ±0.19

Port 4b AXIAL LOCATION Z/L = 0.73; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
12.53	0.008	0.047	0.042	6.44
12.55	0.007	0.048	0.043	6.43
12.23	0.007	0.043	0.041	6.56
12.37	0.006	0.044	0.043	6.69
12.43	0.007	0.044	0.043	6.54
12.51	0.007	0.053	0.044	6.46
12.44 ±0.12	0.007 ±0.001	0.046 ±0.004	0.043 ±0.001	6.52 ±0.10

Port 5b AXIAL LOCATION Z/L = 0.89; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.83	0.005	0.080	0.049	5.05
13.78	0.005	0.083	0.049	4.96
13.73	0.005	0.088	0.049	5.03
13.73	0.005	0.086	0.050	5.03
13.68	0.005	0.089	0.049	5.04
13.65	0.005	0.089	0.050	5.16
13.68	0.005	0.075	0.050	5.17
13.73	0.004	0.076	0.051	5.02
13.80	0.004	0.075	0.051	4.97
13.78	0.004	0.084	0.052	4.89
13.74 ±0.06	0.005 ±0.001	0.082 ±0.006	0.050 ±0.001	5.03 ±0.08

BREECHING AXIAL LOCATION Z/L = 1.21; r/R = 0

CO_2	CO	SO_2 /[%]	NO_x	O_2
13.74	0.004	0.091	0.050	4.96
13.77	0.003	0.092	0.049	4.85
13.65	0.003	0.088	0.049	4.76
13.85	0.004	0.089	0.050	4.82
13.86	0.003	0.095	0.049	4.78
13.85	0.004	0.098	0.048	4.81
13.74	0.004	0.097	0.048	4.90
13.91	0.003	0.092	0.049	4.75
13.90	0.003	0.090	0.049	4.70
13.85	0.003	0.086	0.048	4.72
13.89	0.004	0.088	0.048	4.73
13.85	0.004	0.092	0.048	4.71
13.90	0.003	0.089	0.048	4.71
13.56	0.006	0.076	0.048	5.38
13.62	0.005	0.077	0.048	5.38
13.80 ±0.11	0.004 ±0.001	0.089 ±0.006	0.049 ±0.001	4.86 ±0.22

APPENDIX VIII:

Stoichiometric combustion claculations with vitiated air

TEST 1 3B VIT-AIR

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.8302	C+O2=CO2	2.2138	3.0440			
H2	0.1056	H2+.5O2=H2	0.8448		0.9504		
O2	0.0150		-0.0150				
S	0.0207	S+O2=SO2	0.0207			0.0414	
N2	0.0045						0.0045
H2O	0.0240				0.0240		
ASH	0.0000						
TOTAL	1.0000		3.0643	3.0440	0.9744	0.0414	0.0045

3.0643 KG OF O2/ KG OF FUEL TRANSL. TO 14.0825 KG V-AIR /KG FUEL

N2 SUPPL'D 10.8494 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	3.2172	44.0000	0.5090	1.6378	1.6378	14.1875	15.8526
H2O	0.9744	18.0000	1.2444	1.2125		10.5035	
SO2	0.0414	64.0000	0.3500	0.0144	0.0144	0.1255	0.1402
N2	10.8494	28.0000	0.8000	8.6795	8.6795	75.1833	84.0071
TOTAL	15.0825			11.5445	10.3319	99.9999	99.9999

IF WE HAVE 5.4800 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RRM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	3.2172	44.0000	0.5090	1.6378	1.6378	10.7815	11.7168
H2O	0.9744	18.0000	1.2444	1.2125		7.9819	
SO2	0.0414	64.0000	0.3500	0.0144	0.0144	0.0953	0.1036
O2	1.0940	32.0000	0.7000	0.7658	0.7658	5.0412	5.4785
N2	14.4509	28.0000	0.8000	11.5607	11.5607	76.0997	82.7009
TOTAL	19.7780			15.1915	13.9789	100.0000	99.9999

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0040 % O2= 5.4800 % N2= 82.4670

CO2= 11.9300 % SO2= 930.0000 PPM FLUE GAS TEMP.= 1077.0000

MAXIMUM CO2 = $\frac{1112.4000}{73.8131} = 15.0704\ \%$

VOL OF CO2 = 1.5427 M3

MASS OF CO2 = 3.0309 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.8266 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 99.5680 %

TEST 1 BREECH WITH VIT-AIR

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.8302	C+O2=CO2	2.2138	3.0440			
H2	0.1056	H2+.5O2=H2	0.8448		0.9504		
O2	0.0150		-0.0150				
S	0.0207	S+O2=SO2	0.0207			0.0414	
N2	0.0045						0.0045
H2O	0.0240				0.0240		
ASH	0.0000						
TOTAL	1.0000		3.0643	3.0440	0.9744	0.0414	0.0045

3.0643 KG OF O2/ KG OF FUEL TRANSL. TO 14.0825 KG V-AIR /KG FUEL

N2 SUPPL'D 10.8494 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	3.2172	44.0000	0.5090	1.6378	1.6378	14.1875	15.8526
H2O	0.9744	18.0000	1.2444	1.2125		10.5035	
SO2	0.0414	64.0000	0.3500	0.0144	0.0144	0.1255	0.1402
N2	10.8494	28.0000	0.8000	8.6795	8.6795	75.1833	84.0071
TOTAL	15.0825			11.5445	10.3319	99.9999	99.9999

IF WE HAVE 5.0200 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	3.2172	44.0000	0.5090	1.6378	1.6378	11.0747	12.0639
H2O	0.9744	18.0000	1.2444	1.2125		8.1990	
SO2	0.0414	64.0000	0.3500	0.0144	0.0144	0.0979	0.1067
O2	0.9734	32.0000	0.7000	0.6813	0.6813	4.6072	5.0187
N2	14.0537	28.0000	0.8000	11.2429	11.2429	76.0209	82.8105
TOTAL	19.2602			14.7893	13.5767	99.9999	99.9999

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0030 % O2= 5.0200 % N2= 82.5700

CO2= 12.2500 % SO2= 1320.0000 PPM FLUE GAS TEMP.= 1004.0000

MAXIMUM CO2 = $\frac{1144.300)}{76.0100}$ = 15.0545 %

VOL OF CO2 = 1.5408 M3

MASS OF CO2 = 3.0271 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.8255 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 99.4444 %

TEST2 3B VIT-AIR

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.8302	C+O2>CO2	2.2138	3.0440			
H2	0.1056	H2+.5O2>H2	0.8448		0.9504		
O2	0.0150		-0.0150				
S	0.0207	S+O2>SO2	0.0207			0.0414	
N2	0.0045						0.0045
H2O	0.0240				0.0240		
ASH	0.0000						
TOTAL	1.0000		3.0643	3.0440	0.9744	0.0414	0.0045

3.0643 KG OF O2/ KG OF FUEL TRANSL. TO 14.0825 KG V-AIR /KG FUEL

N2 SUPPL'D 10.8494 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	3.2172	44.0000	0.5090	1.6378	1.6378	14.1875	15.8526
H2O	0.9744	18.0000	1.2444	1.2125		10.5035	
SO2	0.0414	64.0000	0.3500	0.0144	0.0144	0.1255	0.1402
N2	10.8494	28.0000	0.8000	8.6795	8.6795	75.1833	84.0071
TOTAL	15.0825			11.5445	10.3319	99.9999	99.9999

IF WE HAVE 5.0800 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	3.2172	44.0000	0.5090	1.6378	1.6378	11.0366	12.0186
H2O	0.9744	18.0000	1.2444	1.2125		8.1707	
SO2	0.0414	64.0000	0.3500	0.0144	0.0144	0.0976	0.1063
O2	0.9887	32.0000	0.7000	0.6921	0.6921	4.6637	5.0787
N2	14.1042	28.0000	0.8000	11.2834	11.2834	76.0311	82.7962
TOTAL	19.3260			14.8404	13.6279	99.9999	100.0000

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0020 % O2= 5.0800 % N2= 82.7150

CO2= 12.0600 % SO2= 1140.0000 PPM FLUE GAS TEMP.= 1019.0000

MAXIMUM CO2 = 1125.2000 / 75.7213 = 14.8597 %

VOL OF CO2 = 1.5173 M3

MASS OF CO2 = 2.9811 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.8130 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 97.9327 %

TEST 2 BREECH VIT-AIR

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.8302	C+O2>CO2	2.2138	3.0440			
H2	0.1056	H2+.5O2>H2	0.8448		0.9504		
O2	0.0150		-0.0150				
S	0.0207	S+O2>SO2	0.0207			0.0414	
N2	0.0043						0.0045
H2O	0.0240				0.0240		
ASH	0.0000						
TOTAL	1.0000		3.0643	3.0440	0.9744	0.0414	0.0045

3.0643 KG OF O2/ KG OF FUEL TRANSL. TO 14.0825 KG V-AIR /KG FUEL

N2 SUPPL'D 10.8494 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	3.2172	44.0000	0.5090	1.6378	1.6378	14.1875	15.8526
H2O	0.9744	18.0000	1.2444	1.2125		10.5035	
SO2	0.0414	64.0000	0.3500	0.0144	0.0144	0.1255	0.1402
N2	10.8494	28.0000	0.8000	8.6795	8.6795	75.1833	84.0071
TOTAL	15.0825			11.5445	10.3319	99.9999	99.9999

IF WE HAVE 5.5100 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RRM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	3.2172	44.0000	0.5090	1.6378	1.6378	10.7624	11.6941
H2O	0.9744	18.0000	1.2444	1.2125		7.9678	
SO2	0.0414	64.0000	0.3500	0.0144	0.0144	0.0952	0.1034
O2	1.1021	32.0000	0.7000	0.7715	0.7715	5.0696	5.5085
N2	14.4776	28.0000	0.8000	11.5820	11.5820	76.1049	82.6938
TOTAL	19.8128			15.2185	14.0059	100.0000	99.9999

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0020 % O2= 5.5100 % N2= 82.6310

CO2= 11.6500 % SO2= 1190.0000 PPM FLUE GAS TEMP.= 998.0000

MAXIMUM CO2 = 1084.2000 / 73.6659 = 14.7177 %

VOL OF CO2 = 1.5004 M3

MASS OF CO2 = 2.9477 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.8039 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 96.8357 %

TEST 3 1B VIT-AIR CWM

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.5945	C+O2>CO2	1.5853	2.1798			
H2	0.0383	H2+.5O2>H2	0.3064		0.3447		
O2	0.0366		-0.0366				
S	0.0070	S+O2>SO2	0.0070			0.0140	
N2	0.0103						0.0103
H2O	0.3030				0.3030		
ASH	0.0102						
TOTAL	0.9999		1.8621	2.1798	0.6477	0.0140	0.0103

1.8621 KG OF O2/ KG OF FUEL TRANSL. TO 8.5575 KG V-AIR /KG FUEL

N2 SUPPL'D 6.6005 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	16.0354	18.0398
H2O	0.6477	18.0000	1.2444	0.8060		11.1104	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0675	0.0759
N2	6.6005	28.0000	0.8000	5.2804	5.2804	72.7864	81.8842
TOTAL	9.5472			7.2546	6.4486	100.0000	100.0000

IF WE HAVE 4.0500 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RRM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	13.2268	14.5612
H2O	0.6477	18.0000	1.2444	0.8060		9.1644	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0557	0.0613
O2	0.4621	32.0000	0.7000	0.3234	0.3234	3.6781	4.0491
N2	8.1217	28.0000	0.8000	6.4974	6.4974	73.8749	81.3281
TOTAL	11.5306			8.7951	7.9891	100.0000	100.0000

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0170 % O2= 4.0500 % N2= 81.5780

CO2= 14.2400 % SO2= 440.0000 PPM FLUE GAS TEMP.= 1371.0000

MAXIMUM CO2 = 1344.7000 16.6684 %

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80.6731

VOL OF CO2 = 1.0572 M3

MASS OF CO2 = 2.0770 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.5664 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 95.2831 %

TEST 3 2B VIT-AIR CWM

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.5945	C+O2>CO2	1.5853	2.1798			
H2	0.0383	H2+.5O2>H2	0.3064		0.3447		
O2	0.0366		-0.0366				
S	0.0070	S+O2>SO2	0.0070			0.0140	
N2	0.0103						0.0103
H2O	0.3030				0.3030		
ASH	0.0102						
TOTAL	0.9999		1.8621	2.1798	0.6477	0.0140	0.0103

1.8621 KG OF O2/ KG OF FUEL TRANSL. TO 8.5575 KG V-AIR /KG FUEL

N2 SUPPL'D 6.6005 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	16.0354	18.0398
H2O	0.6477	18.0000	1.2444	0.8060		11.1104	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0675	0.0759
N2	6.6005	28.0000	0.8000	5.2804	5.2804	72.7864	81.9842
TOTAL	9.5472			7.2546	6.4486	100.0000	100.0000

IF WE HAVE 3.7700 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	13.4249	14.8017
H2O	0.6477	18.0000	1.2444	0.8060		9.3016	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0565	0.0623
O2	0.4242	32.0000	0.7000	0.2962	0.2962	3.4186	3.7693
N2	7.9936	28.0000	0.8000	6.3943	6.3948	73.7981	81.3666
TOTAL	11.3634			8.6653	7.8593	100.0000	100.0000

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0120 % O2= 3.7700 % N2= 81.7940

CO2= 14.2800 % SO2= 720.0000 PPM FLUE GAS TEMP.= 1265.0000

MAXIMUM CO2 = 1348.2000 16.4410 %

= 82.0020

VOL OF CO2 = 1.0399 M3

MASS OF CO2 = 2.0430 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.5572 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 93.7271 %

TEST3 3B VIT-AIR CWM

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.5945	C+O2>CO2	1.5853	2.1798			
H2	0.0383	H2+.5O2>H2O	0.3064		0.3447		
O2	0.0366		-0.0366				
S	0.0070	S+O2>SO2	0.0070			0.0140	
N2	0.0103						0.0103
H2O	0.3030				0.3030		
ASH	0.0102						
TOTAL	0.9999		1.8621	2.1798	0.6477	0.0140	0.0103

1.8621 KG OF O2/ KG OF FUEL TRANSL. TO 8.5575 KG V-AIR /KG FUEL

N2 SUPPL'D 6.6005 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	16.0354	18.0398
H2O	0.6477	18.0000	1.2444	0.8060		11.1104	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0675	0.0759
N2	6.6005	28.0000	0.8000	5.2804	5.2804	72.7864	81.8842
TOTAL	9.5472			7.2546	6.4486	100.0000	100.0000

IF WE HAVE 4.1200 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	13.1772	14.5011
H2O	0.6477	18.0000	1.2444	0.8060		9.1300	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0559	0.0610
O2	0.4720	32.0000	0.7000	0.3304	0.3304	3.7430	4.1191
N2	8.1544	28.0000	0.8000	6.5235	6.5235	73.8941	81.3185
TOTAL	11.5733			8.8282	8.0222	100.0000	99.9999

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0070 % O2= 4.1200 % N2= 81.5900

CO2= 14.1600 % SO2= 550.0000 PPM FLUE GAS TEMP.= 1218.0000

MAXIMUM CO2 = 1335.7000 16.6298 %

80.3196

VOL OF CO2 = 1.0542 M3

MASS OF CO2 = 2.0712 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.5648 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 95.0178 %

TEST 3 4B VIT-AIR CWM

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.5945	C+O2 CO2	1.5853	2.1798			
H2	0.0383	H2+.5O2 H2	0.3064		0.3447		
O2	0.0366		-0.0366				
S	0.0070	S+O2 SO2	0.0070			0.0140	
N2	0.0103						0.0103
H2O	0.3030				0.3030		
ASH	0.0102						
TOTAL	0.9999		1.8621	2.1798	0.6477	0.0140	0.0103

1.8621 KG OF O2/ KG OF FUEL TRANSL. TO 8.5575 KG V-AIR /KG FUEL

N2 SUPPL'D 6.6005 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	16.0354	18.0398
H2O	0.6477	18.0000	1.2444	0.8060		11.1104	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0675	0.0759
N2	6.6005	28.0000	0.8000	5.2804	5.2804	72.7864	81.8842
TOTAL	9.5472			7.2546	6.4486	100.0000	100.0000

IF WE HAVE 3.8600 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	13.3613	14.7244
H2O	0.6477	18.0000	1.2444	0.8060		9.2576	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0562	0.0620
O2	0.4355	32.0000	0.7000	0.3049	0.3049	3.5019	3.8592
N2	8.0343	28.0000	0.8000	6.4274	6.4274	73.8227	81.3542
TOTAL	11.4167			8.7066	7.9006	100.0000	100.0000

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0050 % O2= 3.8600 % N2= 81.6140

CO2= 14.3900 % SO2= 650.0000 PPM FLUE GAS TEMP.= 1153.0000

MAXIMUM CO2 = 1358.5000 16.6567 %

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81.5584

VOL OF CO2 = 1.0563 M3

MASS OF CO2 = 2.0752 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.5659 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 95.2024 %

TEST 3 SB VIT-AIR CUM

STOICH. COMBUSTION CALC'N

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.5945	C+O2=CO2	1.5853	2.1798			
H2	0.0383	H2+.5O2=H2	0.3064		0.3447		
O2	0.0366		-0.0366				
S	0.0070	S+O2=SO2	0.0070			0.0140	
N2	0.0103						0.0103
H2O	0.3030				0.3030		
ASH	0.0102						
TOTAL	0.9999		1.8621	2.1798	0.6477	0.0140	0.0103

1.8621 KG OF O2/ KG OF FUEL TRANSL. TO 8.5575 KG V-AIR /KG FUEL

N2 SUPPL'D 6.6005 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	16.0354	18.0398
H2O	0.6477	18.0000	1.2444	0.8060		11.1104	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0675	0.0759
N2	6.6005	28.0000	0.8000	5.2804	5.2804	72.7864	81.8842
TOTAL	9.5472			7.2546	6.4486	100.0000	100.0000

IF WE HAVE 2.8600 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	14.0646	15.5832
H2O	0.6477	18.0000	1.2444	0.8060		9.7449	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0592	0.0656
O2	0.3049	32.0000	0.7000	0.2134	0.2134	2.5809	2.8595
N2	7.6043	28.0000	0.8000	6.0835	6.0835	73.5502	81.4915
TOTAL	10.8561			8.2712	7.4652	100.0000	100.0000

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0050 % O2= 2.8600 % N2= 81.8570

CO2= 15.1500 % SO2= 640.0000 PPM FLUE GAS TEMP.= 1084.0000

MAXIMUM CO2 = 1434.5000 16.6148 %

86.3386 =

VOL OF CO2 = 1.0531 M3

MASS OF CO2 = 2.0689 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.5642 KG/KG FUEL

CARBON CONVERSION EFFICIENCY = 94.9151 %

TEST3 BREECH VIT-AIR CWM

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.5945	C+O2>CO2	1.5853	2.1798			
H2	0.0383	H2+.5O2>H2	0.3064		0.3447		
O2	0.0366		-0.0366				
S	0.0070	S+O2>SO2	0.0070			0.0140	
N2	0.0103						0.0103
H2O	0.3030				0.3030		
ASH	0.0102						
TOTAL	0.9999		1.8621	2.1798	0.6477	0.0140	0.0103

1.8621 KG OF O2/ KG OF FUEL TRANSL. TO 8.5575 KG V-AIR /KG FUEL

N2 SUPPL'D 6.6005 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	16.0354	18.0398
H2O	0.6477	18.0000	1.2444	0.8060		11.1104	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0675	0.0759
N2	6.6005	28.0000	0.8000	5.2804	5.2804	72.7864	81.8842
TOTAL	9.5472			7.2546	6.4486	100.0000	100.0000

IF WE HAVE 3.1000 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	13.8965	15.3771
H2O	0.6477	18.0000	1.2444	0.8060		9.6284	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0585	0.0647
O2	0.3349	32.0000	0.7000	0.2344	0.2344	2.8010	3.0995
N2	7.7032	28.0000	0.8000	6.1625	6.1625	73.6155	81.4585
TOTAL	10.9849			8.3712	7.5652	100.0000	100.0000

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0040 % O2= 3.1000 % N2= 81.8370

CO2= 14.9300 % SO2= 660.0000 PPM FLUE GAS TEMP.= 972.0000

MAXIMUM CO2 = 1412.4000 / 85.1895 = 16.5794 %

VOL OF CO2 = 1.0504 M3

MASS OF CO2 = 2.0637 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.5628 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 94.6732 %

TEST 4 1B VIT-AIR CWM

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.5945	C+O2>CO2	1.585-	2.1798			
H2	0.0383	H2+.5O2>H2O	0.3064		0.3447		
O2	0.0366		-0.0366				
S	0.0070	S+O2>SO2	0.0070			0.0140	
N2	0.0103						0.0103
H2O	0.3030				0.3030		
ASH	0.0102						
TOTAL	0.9999		1.8621	2.1798	0.6477	0.0140	0.0103

1.8621 KG OF O2/ KG OF FUEL TRANSL. TO 8.5575 KG V-AIR /KG FUEL

N2 SUPPL'D 6.6005 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	16.0354	18.0398
H2O	0.6477	18.0000	1.2444	0.8060		11.1104	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0675	0.0759
N2	6.6005	28.0000	0.8000	5.2804	5.2804	72.7864	81.8843
TOTAL	9.5472			7.2546	6.4486	100.0000	100.0000

IF WE HAVE 7.0800 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	11.0445	11.9597
H2O	0.6477	18.0000	1.2444	0.8060		7.6523	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0465	0.0503
O2	0.9834	32.0000	0.7000	0.6884	0.6884	6.5359	7.0775
N2	9.8378	28.0000	0.8000	7.8703	7.8703	74.7206	80.9123
TOTAL	13.7681			10.5329	9.7269	99.9999	100.0000

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0140 % O2= 7.0800 % N2= 81.1550

CO2= 11.6500 % SO2= 410.0000 PPM FLUE GAS TEMP.= 1217.0000

MAXIMUM CO2 = 1085.4000 16.3997 %

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66.1840

VOL OF CO2 = 1.0368 M3

MASS OF CO2 = 2.0449 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.5555 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 93.4453 %

TEST 4 2B VIT-AIR CWM

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.5945	C+O2>CO2	1.5853	2.1798			
H2	0.0383	H2+.5O2>H2O	0.3064		0.3447		
O2	0.0366		-0.0366				
S	0.0070	S+O2>SO2	0.0070			0.0140	
N2	0.0103						0.0103
H2O	0.3030				0.3030		
ASH	0.0102						
TOTAL	0.9999		1.8621	2.1798	0.6477	0.0140	0.0103

1.8621 KG OF O2/ KG OF FUEL TRANSL. TO 8.5575 KG V-AIR /KG FUEL

N2 SUPPL'D 6.6005 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	MW	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	16.0354	18.0398
H2O	0.6477	18.0000	1.2444	0.8060		11.1104	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0675	0.0759
N2	6.6005	28.0000	0.8000	5.2804	5.2804	72.7864	81.8842
TOTAL	9.5472			7.2546	6.4486	100.0000	100.0000

IF WE HAVE 7.8400 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	MW	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	10.4858	11.3073
H2O	0.6477	18.0000	1.2444	0.8060		7.2652	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0441	0.0476
O2	1.1518	32.0000	0.7000	0.8062	0.8062	7.2676	7.8369
N2	10.3921	28.0000	0.8000	8.3136	8.3136	74.9371	80.8080
TOTAL	14.4907			11.0942	10.2881	99.9999	100.0000

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0140 % O2= 7.8400 % N2= 80.9700

CO2= 11.0700 % SO2= 630.0000 PPM FLUE GAS TEMP.= 1191.0000

MAXIMUM CO2 = 1027.4000 / 62.5512 = 16.4249 %

VOL OF CO2 = 1.0387 M3

MASS OF CO2 = 2.0406 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.5565 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 93.6172 %

TEST 4 5B VIT-AIR+ CWM

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.5945	C+O2 CO2	1.5853	2.1798			
H2	0.0383	H2+.5O2 H2O	0.3064		0.3447		
O2	0.0366		-0.0366				
S	0.0070	S+O2 SO2	0.0070			0.0140	
N2	0.0103						0.0103
H2O	0.3036				0.3036		
ASH	0.0103						
TOTAL	0.9999		1.8621	2.1798	0.6483	0.0140	0.0103

1.8621 KG OF O2/ KG OF FUEL TRANSL. TO 8.5575 KG V-AIR /KG FUEL

N2 SUPPLIED 6.6005 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	MWM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	16.0354	18.0378
H2O	0.6477	18.0000	1.2444	0.8060		11.1104	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0675	0.0759
N2	6.6005	28.0000	0.8000	5.2804	5.2804	72.7867	81.8863
TOTAL	9.5472			7.2546	6.4486	100.0000	100.0000

IF WE HAVE 6.6800 PERCENT EXCESS O2 FLUE GA ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	MWM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	11.3367	12.3031
H2O	0.6477	18.0000	1.2444	0.8060		7.8548	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0477	0.0518
O2	0.9020	32.0000	0.7000	0.6314	0.6314	6.1532	6.6778
N2	9.5697	28.0000	0.8000	7.6558	7.6558	74.6075	80.9672
TOTAL	13.4186			10.2615	9.4554	100.0000	100.0000

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0110 % O2= 6.6800 % N2= 81.0670

CO2= 12.1600 % SO2= 340.0000 PPM FLUE GAS TEMP.= 1141.0000

MAXIMUM CO2 = 1136.1000 / 68.0903 = 16.6851 %

VOL OF CO2 = 1.0584 M3

MASS OF CO2 = 2.0795 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.5671 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 95.3975 %

TEST 4 3B VIT-AIR CWM

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.5945	C+02 CO2	1.5853	2.1798			
H2	0.0383	H2+.502 H2	0.30		0.3447		
O2	0.0366		-0.0366				
S	0.0070	S+02 SO2	0.0070			0.0140	
N2	0.0103						0.0103
H2O	0.3030				0.3030		
ASH	0.0102						
TOTAL	0.9999		1.8621	2.1798	0.6477	0.0140	0.0103

1.8621 KG OF O2/ KG OF FUEL TRANSL. TO 8.3575 KG V-AIR /KG FUEL

N2 SUPPL'D 6.6005 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	16.0354	18.0398
H2O	0.6477	18.0000	1.2444	0.8060		11.1104	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0675	0.0759
N2	6.6005	28.0000	0.8000	5.2804	5.2804	72.7864	81.8842
TOTAL	9.5472			7.2546	6.4486	100.0000	100.0000

IF WE HAVE 5.8400 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	11.9462	13.0243
H2O	0.6477	18.0000	1.2444	0.8060		8.2771	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0503	0.0548
O2	0.7449	32.0000	0.7000	0.5214	0.5214	5.3550	5.8383
N2	9.0527	28.0000	0.8000	7.2422	7.2422	74.3711	81.0825
TOTAL	12.7445			9.7379	8.9319	100.0000	100.0000

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0060 % O2= 5.8400 % N2= 81.1510

CO2= 12.8500 % SO2= 950.0000 PPM FLUE GAS TEMP.= 1120.0000

MAXIMUM CO2 = 1204.6000 / 72.0961 = 16.7082 %

VOL OF CO2 = 1.0602 M3

MASS OF CO2 = 2.0829 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.5680 KG/KG FUEL

CARBON CONVERSION EFFICIENCY = 95.5559 %

TEST 4 SB VIT-AIR CWM

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.5945	C+O2 CO2	1.5853	2.1798			
H2	0.0383	H2+.5O2 H2	0.3064		0.3447		
O2	0.0366		-0.0366				
S	0.0070	S+O2 SO2	0.0070			0.0140	
N2	0.0103						0.0103
H2O	0.3030				0.3030		
ASH	0.0102						
TOTAL	0.9999		1.8621	2.1798	0.6477	0.0140	0.0103

1.8621 KG OF O2/ KG OF FUEL TRANSL. TO 8.5575 KG V-AIR /KG FUEL

N2 SUPPL'D 6.6005 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	16.0354	18.0398
H2O	0.6477	18.0000	1.2444	0.8060		11.1104	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0675	0.0759
N2	6.6005	28.0000	0.8000	5.2804	5.2804	72.7864	81.8842
TOTAL	9.5472			7.2546	6.4486	100.0000	100.0000

IF WE HAVE 5.2500 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	12.3710	13.5308
H2O	0.6477	18.0000	1.2444	0.8060		8.5715	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0521	0.0569
O2	0.6446	32.0000	0.7000	0.4512	0.4512	4.7987	5.2486
N2	8.7225	28.0000	0.8000	6.9780	6.9780	74.2065	81.1634
TOTAL	12.3139			9.4035	8.5975	100.0000	100.0000

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0060 % O2= 5.2500 % N2= 81.1500

CO2= 13.4400 % SO2= 940.0000 PPM FLUE GAS TEMP.= 1181.0000

MAXIMUM CO2 = 1263.6000 16.8668 %

= 74.9163

VOL OF CO2 = 1.0723 M3

MASS OF CO2 = 2.1067 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.5745 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 96.6468 %

TEST 4 BREECH VIT-AIR CWM

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.5945	C+O2 CO2	1.5853	2.1798			
H2	0.0383	H2+.5O2 H2	0.3064		0.3447		
O2	0.0366		-0.0366				
S	0.0070	S+O2 SO2	0.0070			0.0140	
N2	0.0103						0.0103
H2O	0.3030				0.3030		
ASH	0.0102						
TOTAL	0.9999		1.8621	2.1798	0.6477	0.0140	0.0103

1.8621 KG OF O2/ KG OF FUEL TRANSL. TO 8.5575 KG V-AIR /KG FUEL

N2 SUPPL'D 6.6005 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	16.0354	18.0398
H2O	0.6477	18.0000	1.2444	0.8060		11.1104	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0675	0.0759
N2	6.6005	28.0000	0.8000	5.2804	5.2804	72.7864	81.8842
TOTAL	9.5472			7.2546	6.4486	100.0000	100.0000

IF WE HAVE 4.9300 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	12.6003	13.8056
H2O	0.6477	18.0000	1.2444	0.8060		8.7303	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0530	0.0581
O2	0.5933	32.0000	0.7000	0.4153	0.4153	4.4985	4.9288
N2	8.5535	28.0000	0.8000	6.8428	6.8428	74.1176	81.2074
TOTAL	12.0936			9.2324	8.4264	100.0000	99.9999

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0050 % O2= 4.9300 % N2= 81.3410

CO2= 13.6000 % SO2= 630.0000 PPM FLUE GAS TEMP.= 1052.0000

MAXIMUM CO2 = 1279.5000 / 76.4440 = 16.7377 %

VOL OF CO2 = 1.0624 M3

MASS OF CO2 = 2.0873 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.5692 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 95.7585 %

TEST 2 LB WIT-AIR 1WM

STOICH. COMBUSTION CAL

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	CO2	PRODUCTS KG/KG FUEL H2O	SO2	N2
C	0.5945	C+O2 CO2	1.5853	2.1798			
H2	0.0383	H2+.5O2 H2O	0.3064		0.3447		
O2	0.0366		-0.0366				
S	0.0070	S+O2 SO2	0.0070			0.0140	
N2	0.0103						0.0103
H2O	0.3030				0.3030		
ASH	0.0102						
TOTAL	0.9999		1.8621	2.1798	0.6477	0.0140	0.0103

1.8621 KG OF O2/ KG OF FUEL TRANSL. TO 8.5575 KG V-AIR /KG FUEL

N2 SUPPL'D 6.6005 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	16.0354	18.0398
H2O	0.6477	18.0000	1.2444	0.8060		11.1104	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0675	0.0759
N2	6.6005	28.0000	0.8000	5.2804	5.2804	72.7864	81.8842
TOTAL	9.5472			7.2546	6.4486	100.0000	100.0000

IF WE HAVE 8.6600 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	9.8777	10.6034
H2O	0.6477	18.0000	1.2444	0.8060		6.8439	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0416	0.0446
O2	1.3567	32.0000	0.7000	0.9494	0.9496	8.0638	8.6563
N2	11.0663	28.0000	0.8000	8.8532	8.8532	75.1727	80.6955
TOTAL	15.3700			11.7771	10.9711	100.0000	99.9999

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0100 % O2= 8.6600 % N2= 80.9860

CO2= 10.2700 % SO2= 310.0000 PPM FLUE GAS TEMP.= 1130.0000

MAXIMUM CO2 = 947.0000 16.1537 %

58.6241

VOL OF CO2 = 1.0182 M3

MASS OF CO2 = 2.0005 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.5455 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 91.7739 %

TEST 5 48 VIT-AIR CWM

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.5945	C+O2>CO2	1.5853	2.1798			
H2	0.0383	H2+.5O2>H2O	0.3064		0.3447		
O2	0.0366		-0.0366				
S	0.0070	S+O2>SO2	0.0070			0.0140	
N2	0.0103						0.0103
H2O	0.3030				0.3030		
ASH	0.0102						
TOTAL	0.9999		1.8621	2.1798	0.6477	0.0140	0.0103

1.8621 KG OF O2/ KG OF FUEL TRANSL. TO 8.5575 KG V-AIR /KG FUEL

N2 SUPPL'D 6.6005 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	16.0354	18.0398
H2O	0.6477	18.0000	1.2444	0.8060		11.1104	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0675	0.0759
N2	6.6005	28.0000	0.8000	5.2804	5.2804	72.7864	81.8842
TOTAL	9.5472			7.2546	6.4486	100.0000	100.0000

IF WE HAVE 6.5200 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	11.4532	12.4404
H2O	0.6477	18.0000	1.2444	0.8060		7.9355	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0482	0.0524
O2	0.8707	32.0000	0.7000	0.6094	0.6094	6.0006	6.5179
N2	9.4666	28.0000	0.8000	7.5733	7.5733	74.5622	80.9891
TOTAL	13.2841			10.1570	9.3510	99.9999	100.0000

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0070 % O2= 6.5200 % N2= 80.9440

CO2= 12.4400 % SO2= 460.0000 PPM FLUE GAS TEMP.= 1013.0000

MAXIMUM CO2 = 1163.7000 / 68.8476 = 16.9025 %

VOL OF CO2 = 1.0750 M3

MASS OF CO2 = 2.1121 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.5760 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 96.8931 %

TEST 5 BREECH VIT-AIR CWM

STOICH. COMBUSTION CALCS

COMPONENT	KG/KG FUEL	REACTION	O2 REQ'D KG/KG FUEL	PRODUCTS KG/KG FUEL CO2	H2O	SO2	N2
C	0.5945	C+O2>CO2	1.5853	2.1798			
H2	0.0383	H2+.5O2>H2O	0.3064		0.3447		
O2	0.0366		-0.0366				
S	0.0070	S+O2>SO2	0.0070			0.0140	
N2	0.0103						0.0103
H2O	0.3030				0.3030		
SH	0.0102						
TOTAL	0.9999		1.8621	2.1798	0.6477	0.0140	0.0103

1.8621 KG OF O2/ KG OF FUEL TRANSL. TO 8.5575 KG V-AIR /KG FUEL

N2 SUPPL'D 6.6005 KG OF N2/ KG OF FUEL

PRODUCTS	KG/KGFUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	16.0394	18.0398
H2O	0.6477	18.0000	1.2444	0.8060		11.1104	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0675	0.0759
N2	6.6005	28.0000	0.8000	5.2804	5.2804	72.7864	81.8842
TOTAL	9.5472			7.2546	6.4486	100.0000	100.0000

IF WE HAVE 4.8600 PERCENT EXCESS O2 FLUE GAS ANALYSIS BECOMES

PRODUCTS	KG/KG FUEL	RMM	SPEC. VOL. M3/KG	VOL AT STP WET (M3)	VOL AT STP DRY (M3)	PERCENTAGE BY VOLUME WET	DRY
CO2	2.2850	44.0000	0.5090	1.1633	1.1633	12.6504	13.8657
H2O	0.6477	18.0000	1.2444	0.8060		8.7650	
SO2	0.0140	64.0000	0.3500	0.0049	0.0049	0.0532	0.0584
O2	0.5823	32.0000	0.7000	0.4076	0.4076	4.4329	4.8588
N2	8.5175	28.0000	0.8000	6.8110	6.8140	74.0982	81.2170
TOTAL	12.0466			9.1959	8.3898	100.0000	100.0000

FLUE GAS ANALYSIS OF TEST IS

CO= 0.0040 % O2= 4.8600 % N2= 81.1980

CO2= 13.8000 % SO2= 890.0000 PPM FLUE GAS TEMP.= 1037.0000

MAXIMUM CO2 = 1299.4000 16.9243 %

76.7767

VOL OF CO2 = 1.0767 M3

MASS OF CO2 = 2.1153 KG/KG FUEL

CARBON IN THE FUEL BURNT = 0.5769 KG/KG FUEL

CARBON CONVERSION EFFICIENCY 97.0439 %